TRANSPIRATION PERFORMANCE IN BIORETENTION SYSTEMS DESIGNED FOR SEMIARID CLIMATES

by

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ABSTRACT

Bioretention systems have become an increasingly well accepted element of low impact development within stormwater management plans, but much of the research on these systems has taken place in mesic climates. This study examined the effect of vegetative cover on the performance of three 10 m^2 bioretention gardens designed to receive the average annual runoff from a 220 m^2 impervious surface in Salt Lake City, UT for one year beginning January, 2012. Three vegetation options were assessed: no vegetation, wetland vegetation that received irrigation, and an upland plant community that received no irrigation. Each garden was lined and runoff inflow and outflow were measured directly. Gas exchange measurements were taken before and after simulated runoff events and used to quantify transpiration volume. In the upland plant community, shrubs were shown to have higher overall transpiration rates and contributed 60% of the total annual transpiration volume. Grass species demonstrated strong transpiration rate increases in response to simulated runoff events in the summer, especially during the driest months. Total annual transpiration from the upland garden was estimated to be 7% of the inflow volume. The wetland plants were able to transpire a greater volume than the upland plants, roughly 15% of the inflow, but this came at the cost of irrigation demand. ET runoff reductions were measured at 15%, 29% and 39% for the unvegetated, wetland, and upland bioretention gardens, respectively. The high reduction determined for the upland garden may be due to a tear in the liner that resulted in unmeasured outflow. Maximum ET for the upland bioretention garden was deduced using transpiration

measurements and data from the unvegetated plot to be 22% of annual runoff inflow. Soil moisture content data demonstrated localized reduction in soil conductivity in the upland garden throughout the summer, potentially indicating water stress on the plants imposed by the bioretention system design used for this study. It was shown that regionally native plant communities used in bioretention systems can help improve site hydrology while remaining resilient to seasonal runoff inflow fluctuations without requiring supplemental irrigation. This study examined upland shrubs and grasses spaced at native density. However, future research that explores higher plant density and alternative plant communities may yield improvements to bioretention designs that achieve site specific goals for nutrient removal, ET volume reductions, and infiltration.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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INTRODUCTION

In the last century, urbanization has become a dominant worldwide demographic trend. The United Nations reports that in 2010 more than half of the world's population resided in urban areas. In the United States, this number was over 80% for the same year (United Nations, 2012). Both represent a 20% increase from 1950. The U.N. also expects rural populations to decline over the coming decades, meaning that most, if not all, future population growth will occur in urban areas (United Nations, 2012). Increased urbanization has had profound effects on both the natural and built environment.

Urban areas often depend heavily on the water bodies around which they developed for anthropocentric needs that include drinking water, commerce and trade, wastewater conveyance, and recreation. These water bodies also provide crucial ecological services by increasing the biodiversity of local plants and animals, providing quality habitat, and remediating nutrients and pollutants (Costanza *et al.*, 1997; Bolund and Hunhammar, 1999). The manner in which urban regions interact with local water bodies has a great influence on the ability of a lake or river to continue providing quality services. In general, urbanization leads to increased impervious cover types that include roads, rooftops, parking lots, compacted soils, and other land use changes that increase the amount of runoff that follows a storm event (Leopold, 1968). Impervious surfaces enable rapid over-land sheet flow and inhibit infiltration, which causes increased peak discharge rates at urban outfalls, longer flow durations, and ultimately, ecological degradation to receiving water bodies (Leopold, 1968; Booth and Jackson, 1997; Walsh *et al.*, 2005b; Brown *et al.*, 2009).

Water managers have traditionally dealt with this problem using centralized stormwater best management practices (BMPs) to detain or retain excess runoff from urban areas by holding the runoff and controlling its release. Modern discharge orifice designs based on hydrologic simulations are able to effectively reduce peak flow rates for a range of design storms, but concerns remain about the downstream influences of increased high-flow durations and high runoff volumes in urbanized watersheds (Booth and Jackson, 1997; Nehrke and Roesner, 2004; Emerson *et al.*, 2005). In addition, such systems are generally connected to receiving waters through a pipe outfall that bypasses riparian zones, which tends to cause downstream ecological harm simply by changing the discharge hydrologic regime from lateral subsurface flow to surface flow (Booth, 1990; Groffman *et al.*, 2003; Meyer *et al.*, 2005). The combination of centralized detention practices and discharge connection often causes stream water quality issues because the stormwater is routed past plants and soils, which provide opportunities for biological treatment of suspended nutrients and entrapment of hydrocarbons and suspended solids.

In the United States, the need for distributed stormwater infrastructure solutions capable of runoff volume mitigation and preliminary treatment has created a marked increase in acceptance and implementation of low impact development (LID) BMPs to supplement the centralized stormwater infrastructure. LID includes green infrastructure (GI) such as vegetated roofs, bioswales, pervious pavement, rain barrels, and bioretention (USEPA, 2010). Of these GI strategies, bioretention systems in particular have been shown to be highly versatile, and have demonstrated dramatic growth throughout the country since its introduction over a decade ago (Coffman *et al.*, 1993; Prince George's County, 1999; Davis *et al.*, 2001; Hunt *et al.*, 2006; Davis, 2009).

Bioretention systems are designed to work in conjunction with traditional BMP infrastructure to intercept runoff from impervious surfaces using a site-specific combination of vegetation, soil, and gravel drainage. These systems are intended to both reduce runoff volume at the catchment level, and to mitigate nonpoint source pollutants (i.e., nutrients, heavy metals, sediments) by performing preliminary physical and biological treatment. However, detailed performance evaluations needed to inform climate specific design of these systems are still incomplete for many regions of the United States (Davis, 2009). Much of the research to date has been done in mesic climates—regions that receive 750 to 2,000 mm (30 to 80 in) of precipitation per year—where bioretention systems can support plant communities without supplemental irrigation. Several studies performed in mesic climates have demonstrated the ability of bioretention systems to reduce urban runoff volumes and peak flows to approximate predevelopment conditions (Clausen, 2007; Davis, 2008; Hunt, 2008; Shuster *et al.*, 2008). However, bioretention design recommendations for hydrologic restoration are still needed in regions with xeric (arid or semiarid) climates despite the growing need (Davis, 2009; Houdeshel *et al.*, 2012).

The xeric climate regions of the western U.S. fall into two categories: warm deserts and cold deserts. Though the cumulative annual precipitation for both types of desert is similar, the timing of the precipitation makes the hydrology markedly different. In warm desert environments, the majority of annual rainfall occurs in the summer during the growing season allowing much of the total annual precipitation to return to the atmosphere through evapotranspiration (ET), which is the combined processes of soil surface evaporation and plant transpiration, and the rest either collects in streams via overland flow and infiltration, or percolates into groundwater (Young and Nobel, 1986; MacMahon, 2000). In cold deserts, such as the Great Basin Desert that spans most of Nevada and includes the Salt Lake Valley, the majority of annual precipitation falls as snow opposite the growing season and either infiltrates slowly or runs off as it melts in the spring, which results in a smaller fraction of annual precipitation that returns to the atmosphere through ET (MacMahon, 2000; West and Young, 2000). In short, the combination of high temperatures and monsoonal summer rainfall causes the majority of annual precipitation to be returned to the atmosphere through ET in warm deserts. Conversely, precipitation that falls in winter as snow and melts throughout the spring causes most of annual precipitation to be infiltrated in cold deserts.

Some ecologists have already recommended bioretention as an option to restore ET and infiltration hydrologic pathways in urbanized regions dominated by impervious cover (Walsh *et al.*, 2005a; Wenger *et al.*, 2009). Because most of the efforts to quantify the hydrologic function, ET, and infiltration of bioretention systems to date have occurred in systems designed for mesic climates, the bioretention design used for this study employs a regionally native upland plant community designed to minimize maintenance and irrigation in cold desert climates. This system aims to improve catchment-level hydrologic function by restoring the hydrologic pathways of infiltration and evapotranspiration to sites affected by urbanization. This study will explore the influence of different vegetation types on the hydrologic function of bioretention systems implemented in cold desert climates.

BACKGROUND

General Semiarid Plant Transpiration

Plant growth and maintenance requires uptake from two primary pools of resources, one found in the atmosphere, the other found in the soil. To metabolize and use these resources, plants require energy from the sun. From the atmosphere the plant acquires CO_2 and releases water vapor, gas exchange processes known as assimilation and transpiration respectively. From the soil the plant takes up nutrients dissolved in water via bulk flow. Several forces influence the ability of a plant to take up nutrients from the soil and carbon from the atmosphere: (1) the moisture content of the soil, or matric potential; (2) the dryness of the air, or vapor pressure deficit; and (3) the ability of the xylem, the cells that conduct water from root tissue to leaf surface, to resist cavitation. Many plants regulate gas exchange and nutrient uptake by actively adjusting pores, called stomata, on the surface of their leaves. Stomatal regulation and xylem cavitation resistance are two of the primary adaptations that enable semiarid adapted plants to survive in conditions of low soil moisture content and high VPD. Note that some plants are more resistant to fluctuations in water availability than others.

Some plants are adapted to use stomatal regulation to balance the benefits of carbon and nutrient uptake with the costs associated with water loss and risk of xylem cavitation by adjusting stomatal conductance (*gs*). Stomatal conductance is a measure of how freely gasses are exchanged through the surface of the leaf. In general, when water is available the plants will open their stomata to 'spend' water in exchange for growth and maintenance, and when water is scarce the plants will close stomata to conserve water and rely on stored nutrients until water is more readily available. The ability to regulate stomatal conductance is especially useful for plants that have a variable or intermittent water supply.

Research Approach

Overview

The intent of this effort was to assess and quantify the hydrologic performance, specifically evapotranspiration, of a bioretention system that uses semiarid plant vegetation. To this end, system inflow and outflow were quantified to form a coarse water balance. Leaf level gas exchange measurements were recorded before and after growing season runoff events to measure water vapor flux through leaf surfaces in order to refine the water balance and gain a better understanding of the performance of different vegetation types. These values were then scaled by total leaf area to approximate the total transpired volume released by each plant species within the garden.

Research hypothesis

This research is based on the hypothesis that a bioretention garden vegetated with semiarid adapted plants will be capable of capturing, delaying, and reducing stormwater runoff, and that the plant community will be resilient to periodic summer dry periods characteristic of cold desert climates without requiring supplemental irrigation. Secondary research objectives are listed below:

1. ET is a combination of evaporation from the ground surface and the surface of plant leaves, which means that ET is, at least in part, an area dependent aspect of the

hydrologic cycle. Because of these areal dependencies, the 4.5% bioretention garden area to drainage area relationship in this experiment will cause the volume of ET from the surface of each garden to be less than the volume of ET that would result from a natural undisturbed drainage area. However, due to the additional water inputs, the ET volume measured from each garden is expected to be greater than the volume that would leave as ET from a natural undisturbed site of equivalent size.

2. Semiarid vegetation demonstrates resilience to water stress in the summer months and does not require supplemental irrigation. Conversely, the wetland community is expected to require significant irrigation between June and September, and be less resistant to periodic water stress should it occur.

3. The transpiration rate measurements taken before and after simulated runoff pulses are expected to express a meaningful positive response resulting from the increased soil moisture content within the vegetated bioretention gardens. These responses are expected to change throughout the growing season as runoff volume and atmospheric conditions change.

    3a. Due to the physical differences between the grasses and shrubs within the semiarid plant community, it is expected that distinctive transpiration responses will be observed for each plant type. These differences will be the result of access to separate soil moisture profiles, separate strategies for handling periods of water stress, and dissimilar growth patterns.

4. The annual ET volume from the unvegetated bioretention garden is expected to be the lowest of the three bioretention cover types measured in this study because it

represents just the ground surface evaporation component of ET. The annual ET volume from the semiarid plant community is expected to be higher than the unvegetated garden because of the additional transpiration demand imposed by the upland vegetation. The annual ET volume from the wetland community is expected to be higher than the semiarid community because of the additional leaf area, supplemental irrigation, and high water demand of the vegetation.

MATERIALS AND METHODS

Site Description

In 2010, three bioretention gardens were constructed at the Green Infrastructure Research Facility located on the University of Utah campus in the foothills above Salt Lake City, UT, USA (40^o 45' 38", 111^o 49' 50") to assess the differences in evapotranspiration performance between three types of garden cover. Each cell was sized to capture 95% of annual rainfall runoff from a 220 m^2 drainage area, and designed in accordance with recommendations for bioretention design in semiarid and xeric climates from Houdeshel *et al.* (2012). Each bioretention cell measures 2.5 m by 4 m, and was 1.2 m deep. Each garden has a drainage area to garden area ratio (DA:GA) of 22:1 or 4.5% bioretention garden cover. This bioretention design includes a 0.6 m deep storage reservoir composed of 1 cm Utelite gravel (expanded shale, .45 porosity) with a 2.7 m^3 holding capacity that enables storage of the first 1.23 cm of a storm event occurring over the drainage area. The 0.6 m deep topsoil layer was composed of 63% sand, 23% silt, and 14% clay, and was a mixture of soil excavated from the site and topsoil supplied by a local contractor. All three cells were lined with a 40 mil PVC liner, and each has a 1 in drain pipe located at 0.6 m and 1.2 m depths. For this study, the mid-drain pipe was closed and the ball-valve controlling the rate of outflow from the bottom drain was throttled to drain the gardens at approximately 1.5 cm hr^{-1}. This infiltration rate reflects actual infiltration rates measured at two other research sites located on the University of

Utah campus. The soil media, gravel storage layer, drain configuration, and valve control were the same for all three bioretention cells in this study.

Each bioretention garden contains a different plant community. For this effort three bioretention gardens have been established: 1) a wetland community that receives supplemental irrigation, and will be referred to as the "Wetland" garden in this study; 2) an upland adapted plant community that requires no supplemental irrigation in xeric climates, called the "Upland" garden; 3) an unvegetated cell, or "Control" garden. In the Upland and Control gardens, a fabric weed guard was in place at the surface to mitigate invasive species intrusion, and both gardens were covered 6 cm deep with 3 cm light-colored rocks to increase the albedo and reduce surface evaporation. These two gardens also employ a 0.25 m cylindrical forebay composed of the Utelite expanded shale gravel media to reduce ponding duration by conveying a portion of the inflow directly into the gravel storage reservoir below the topsoil. Each forebay was positioned 0.4 m from the garden inlet. The Wetland garden was designed to emulate typical wetland bioretention systems that do not include a forebay, weed guard, or light rock cover.

Garden Vegetation

The Upland garden contained seventeen individual plants from seven different species. The community was a mixture of semiarid adapted shrubs and bunchgrasses and approximates the vegetation density and distribution of natural upland adapted plant communities. These plants are not typically inundated with water, and therefore must be well drained. To accommodate this, the semiarid system eschews surface storage (ponding) and instead moves water into a subsurface gravel storage layer through the gravel forebay, where it was either made available for uptake by deeply rooted plants, or exits the garden via the underdrain. The community composition was designed to make use of two soil moisture profiles: the grasses were expected to have access to the water held in the topsoil, and the shrubs were expected to have access to both the topsoil and water stored in the gravel storage layer. The layout of the Upland garden is shown in Figure 1 and descriptions of the different Upland plant species monitored in this study are shown in Table 1. The Upland garden was continually weeded of undesirable species.

The Wetland garden contained a number of obligate wetland and riparian species. Five of the most prominent species that were monitored for this study are shown in Figure 2 and Table 2. This population was introduced by transplanting several species from a nearby wetland research site that included *S. exigua, Typha sp.*, *J. effuses*, and *Phragmites sp.* These plants had been allowed to establish for two years prior to the beginning of this study. The fifth species monitored in this study, *D. glomerata*, emerged via natural recruitment in the Wetland garden. Weeding was not part of the Wetland management plan, so emergent plant species, including *D. glomerata*, were allowed to grow throughout the growing season.

Synthetic Storms and Irrigation

The region in this study is classified as a semiarid cold desert with a mean annual precipitation of 37 cm that falls opposite the growing season mostly as snow and rain during winter months. Mean monthly precipitation volume and frequency were determined based on a 20-year statistical analysis using records obtained from the National Oceanic and Atmospheric Administration (NOAA) Salt Lake City, UT Airport weather station (Station ID 42-759800) between the years 1990 to 2010. The average

Upland Garden

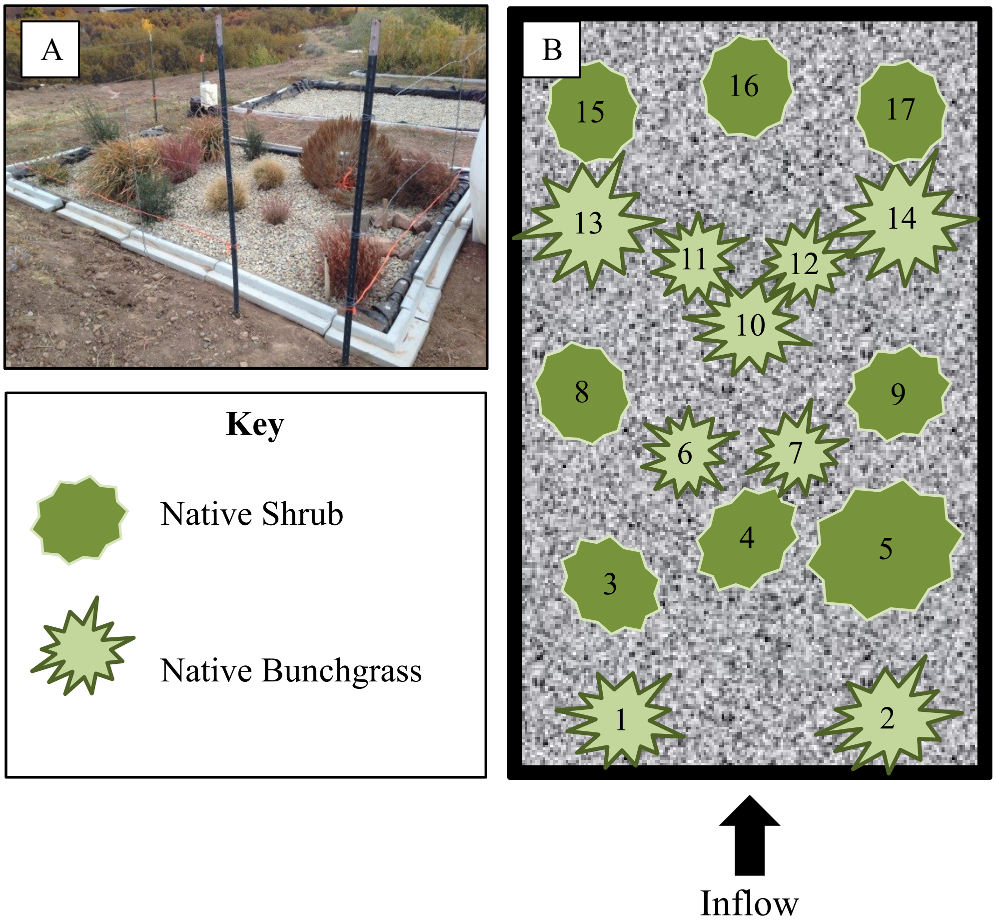

Figure 1. Upland garden overview (A) Photo of Upland garden with fencing to prevent deer herbivory. (B) Upland vegetation layout

Table 1. Upland garden vegetation characteristics

Plant Species	Common Name	ID Numbers	Plant Type
Upland			
Schizachyrium scoparium	Little Bluestem	1, 2, 10	Bunchgrass
Bouteloua gracilis	Blue Gramma	6, 7, 11, 12	Bunchgrass
Sorghastrum nutans	Indiangrass	13, 14	Bunchgrass
Artemisia tridentata	Sagebrush	3, 4	Evergreen Shrub
Artemesia cana	Silver Sagebrush	5	Evergreen Shrub
Cercocarpus ledifolius	Curl-leaf Mahogany	8, 9, 16	Evergreen Shrub
Amelanchier utahensis	Utah Serviceberry	15, 17	Deciduous Shrub

Wetland Garden

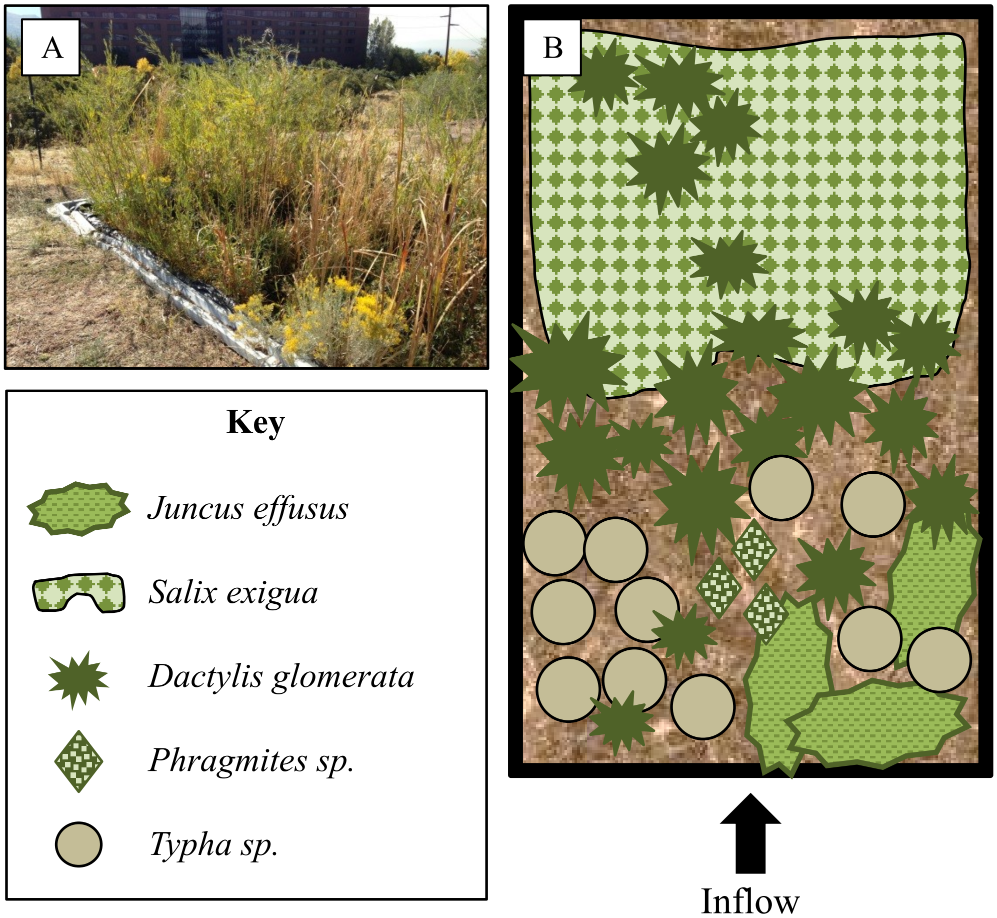

Figure 2. Wetland garden overview (A) Photo of Wetland garden showing *Typha sp.* (right), *S. exigua* (top-center), and *D. glomerata* (low-center). (B) Wetland community approximate layout.

Table 2. Wetland garden vegetation characteristics

Plant Species	Common Name	Plant Type
Wetland		
Juncus effusus	Common Rush	Perennial Grass
Salix exigua	Sandbar Willow	Deciduous Shrub
Dactylis glomerata	Orchard Grass	Perennial Bunchgrass
Phragmites sp.	Common Reed	Perennial Grass
Typha sp.	Common Cattail	Perennial Herb

monthly rainfall depth and frequency for the period of record is shown in Table 3. The runoff volume was determined by scaling the average storm depth by the drainage area of 220 m^2, and was applied to each bioretention garden using 2,080 L water tanks.

In order to mimic the nutrient content of actual storm water runoff, the simulated stormwater was formed by mixing commercial soil amending mulch with tap water at a ratio of 1 kg mulch per 500 L of tap water. The final nutrient concentrations of the simulated storm water were approximately 1.69 mg/l total nitrogen, 1.0 mg/l organic nitrogen, 0.43 mg/l NH_4, 0.29 mg/l NO_x, 0.21 mg/l total phosphorus.

Table 3. Simulated stormwater runoff schedule

Month	[a]Average Number of Storms	Average Total Rainfall (cm)	Average Storm Depth (cm)	[b]Target Storm Volume (L)
January	5	3.33	0.67	1470
February	5	3.25	0.65	1430
March	5	4.39	0.88	1940
April	6	5.23	0.87	1920
May	5	4.39	0.88	1940
June	3	2.72	0.91	2000
July	2	0.09	0.05	100
August	2	1.37	0.69	1510
September	3	2.64	0.88	1940
October	4	3.48	0.87	1920
November	4	3.30	0.83	1820
December	5	2.84	0.57	1250
Total Annual	49	37.03		81,670

Notes: [a] Events defined as 0.254 cm (.1 in) rainfall depth with inter-storm period of 6 hrs
[b] volume computed for 220 m^2 drainage area

Simulated runoff events began January 1, 2012 and continued throughout the year according to the schedule in Table 3. Synthetic storm inflow volume was measured using a GPI^{TM} inline digital flow meter (Great Plains Industries, Wichita, KS) and the duration of each event, or runoff pulse, was between 30-40 minutes depending on the simulated storm volume.

The Upland garden received no supplemental irrigation during this study, but the Wetland garden received irrigation as needed throughout the summer. Approximately 900 L of water was administered per week to the Wetland garden in the months of June through August. Irrigation was ceased during the month of September under the assumption that the increase in simulated storm volume and frequency would be enough to support the Wetland garden community. Incidentally, several species populations in the Wetland garden were reduced in September including *Typha sp.* and *Phragmites sp*. In addition, a mechanical failure interrupted this irrigation schedule during the last two weeks of June and first week of July.

Bioretention System Outflow

The volume of simulated stormwater exiting each garden via the lower underdrain was measured for several days following each simulated storm event by using a custom made tipping bucket and a CR800 data logger. The outflow from the drain of each garden was directed to the tipping bucket via a 1” PVC pipe. Each garden had an independent drain pipe and tipping bucket, and each tipping bucket was calibrated to tip after 3.1 L filled one side.

Soil Moisture Content and Atmospheric Conditions

Soil moisture was continuously monitored every 30 minutes throughout the year of the study using CS616-L soil moisture sensors (Campbell Scientific, Logan, UT). In the Upland and Control gardens, sensors were placed at 10, 30, and 50cm depths and installed as a vertical "stack" of sensors. In the Wetland garden, sensors were placed at 25 and 50cm. The data were recorded with a Campbell Scientific CR210 data logger. Each stack of sensors was located at the center of its respective garden.

A weather station was located 60 m from the bioretention gardens that recorded average humidity and temperatures using instrumentation placed approximately 2 m above the ground surface. Temperature (°C), relative humidity (%), precipitation (mm), and photosynthetically active radiation (PAR) in µmol m^{-2} s^{-1} were stored every 10 minutes by a Campbell CR10X-2M data logger.

Plant Abundance

Leaf area was estimated each month in both of the vegetated gardens. These measurements were necessary to determine fluctuations in plant community and to quantify changes in individual species abundance through the growing season. In this study, leaf area index (LAI) was the measure of a species total leaf area divided by the area of the bioretention garden. This allows for comparisons to be made both between species, to determine abundance, and over time, to determine changes. Total leaf area was also necessary to convert leaf-level transpiration rates into total transpired volume. The gardens monitored for this study are being used for ongoing research, and required a method for scaling leaf area as nondestructively as possible for both the grasses and woody plants.

Grass leaf area

Total leaf area for each grass species was determined by a combination of green blade count, leaf area measurement, and basil area scaling. New blade counts were taken each month for each individual in the Upland and Wetland gardens. Bunchgrass blade count was scaled by a leaf-area to basil area relationship. Each bunchgrass individual was divided into quadrants and the green blades in one quadrant were counted by hand. This number was multiplied by four to obtain a green blade approximation for the whole plant and the basil circumference of bunchgrass was recorded. The blade count was then multiplied by the average area per blade from each plant that was obtained by measurements made by a LI-3100 leaf area meter (Li-Cor, Lincoln, NE). This yielded an estimate of green blade area for each bunchgrass individual. The process was repeated each month in the days following each gas exchange measurement period. A similar method was used for all grass species measured in the Wetland garden.

Woody plant leaf area

For the woody plants, an allometric relationship was formed between stem diameter and leaf area because the two are hydraulically connected, i.e., increased leaf area necessitates the creation of additional stem tissue. If a strong relationship exists between the two, leaf area can be determined indirectly by measuring stem diameter, a much easier measurement to make in the field. All allometric relationships were formed in May of 2012 after each species had fully leafed out. For the *A. utahensis* and *C. ledifolius*, a single representative individual from each species was selected for allometric characterization. Once a relationship was formed, it was used to determine leaf area of the other individuals in the garden of the same species.

The relationships were formed by measuring stem diameter at many locations on a plant stem and counting the number of leaves that were associated with each stem diameter measurement. To further refine this leaf count, small leaves were counted separately from large leaves. Once the average small and large leaf area was determined using the LI-3100 leaf area meter, the total leaf area attributed to each stem diameter reading could be easily scaled by using the small and large leaf count (*A. utahensis* n=8 stems; *C. ledifolius* n=8 stems). This yielded the two values necessary for an allometric relationship function, leaf area and stem diameter. A similar nondestructive method was used to develop allometry for the *S. exigua* (n=9 stems) in the Wetland garden. For *A. cana*, cuttings were taken for a variety of stem diameters (n=15). Each cutting was stripped of its foliage, stem diameter measurements were recorded, and leaf area was measured using the LI-3100.

To scale individual leaf area readings to the whole plot leaf area, a power function regression equation was developed that related stem diameter to leaf area for each of the four woody plant species. New stem diameter measurements were taken each month for each woody plant and the power function was applied to determine leaf area.

Leaf area index

Leaf area index was used in this study to analyze the relative abundance of the plant species within each vegetated garden. Typically, LAI is computed by comparing the total leaf area of a plant's canopy and dividing it by the ground area that it shades. Since the species monitored in this study were small shrubs and grasses, and the bioretention cell plot size was small, comparing canopy leaf area to ground cover would be error prone, making direct comparisons difficult. For this study, LAI was computed using the total one-sided leaf area for each plant species and dividing it by the area of the garden. This gives a ratio of leaf area cover to bioretention plot that can be used to directly compare the relative abundance of each species within each vegetated bioretention garden.

Gas Exchange Analysis

Gas exchange measurements were taken monthly throughout the summer to determine transpiration rate (*E*, mmol H_2O m^{-2} s^{-1}). An open-flow infrared gas analysis (IRGA) system (LI-6400, Li-Cor, Lincoln, NE) was used to make diurnal measurements to determine transpiration responses from each species in the bioretention cells to pulses of stormwater inflow. The IRGA was operated to maintain atmospheric relative humidity and temperature in the chamber and set to hold the in-chamber CO_2 concentration at 400 ppm. An effort was made to achieve stable chamber conditions in less than 1 minute; no reading was recorded if stability could not be attained within that time. A lamp attachment was used as the light source, and photosynthetically active radiation (PAR, μmol m^{-2} s^{-1}) was set to approximate the horizontal incident PAR as read by the external light sensor before each set of readings. A series of diurnal gas exchange readings was taken every other day for five days beginning on the day before the simulated storm event. Each series of gas exchange readings was used to characterize the response of each plant species to the average storm pulse occurring in each month. No readings were taken on a day with a rainfall event, either simulated or natural. The standard gas exchange measurement schedule is shown in Table 4.

For the months of May through August survey measurements were taken every third hour beginning at dawn (0700) and ending after dark (2200) for a total of six

Table 4. Standard gas exchange measurement schedule

Day 1	Day 2	Day 3	Day 4	Day 5
Gas Exchange Measurements	Simulated Storm Event	Gas Exchange Measurements	Irrigate Wetland as needed	Gas Exchange Measurements

measurements $leaf^{-1}$ day^{-1}. Due to instrument maintenance, no gas exchange readings were taken in September. In October, survey measurements were conducted every third hour beginning 0800 and ending at 1900 because of the shortened daylight hours.

In the Upland garden, measurements were taken using the LI-6400 on two leaves per plant, and on two plants per species, for a total of at least four measurements per species (*A. cana* was the only exception because there was only one individual in the Upland garden. Three measurements were taken from this individual to characterize this species). In the Wetland garden, a single leaf was measured from each plant, and three to four plants were measured to characterize the species. No gas exchange readings were taken from the unvegetated Control garden.

Transpiration measurements were averaged to characterize the mean value from each of the eleven species in this study. Because many of the species sampled for this study have small or narrow leaves, all gas exchange values were adjusted for leaf area present in gas exchange chamber by harvesting each leaf and measuring its actual in-chamber area using an LI-3100 (Li-Cor, Lincoln, NE) leaf area meter.

Transpiration Volume

Daily transpired volume (DTV) for each species was estimated using total species leaf area and the transpiration rate values determined using the LI-6400. The gas exchange sampling protocol yielded instantaneous transpiration rate measurements that were separated by known time intervals. DTV was obtained for each plant species by integrating under the curved formed by its diurnal transpiration rate fluctuations, and then scaling by the total leaf area of the species. Transpired volume was computed in liters by assuming density of water at 20 °C (1000 kg m^{-3}) and a molarity of 55.56 mol H_2O L^{-1}.

Transpiration volume for the days between gas exchange measurements were estimated one of three ways: by duplicating the DTV from the day preceding the unknown day; by duplicating the DTV of the day following the unknown day; or by calculating the average of the day preceding and day following the unknown day. On days for which DTV was estimated, the volume was reported for the garden as a whole. In general, for simulated storm events with large runoff volumes, the DTV estimate for Day 2 (see Table 4) was equal to Day 1 to reflect the negative response of semiarid vegetation to inundation. For small or infrequent storm events, the DTV estimate for Day 2 was taken as the mean of Day 1 and Day 3 to reflect the regreening responses that are characteristic of the dry season. Estimates reported for all days following Day 5 were duplicates of the total volume computed for Day 5.

RESULTS

Soil Moisture Content

During the year of monitoring, volumetric soil moisture content data from all three gardens show strong wetting responses to simulated storm events through the spring and fall. For the purposes of this study, a sensor response was defined as a spike in soil moisture content followed by gradual return to prespike water content (Figure 3). Quarterly plots of the soil moisture changes over the full year of 2012 indicated a unique soil moisture pattern for each bioretention garden cover type (Appendix A: Volumetric Soil Moisture Content).

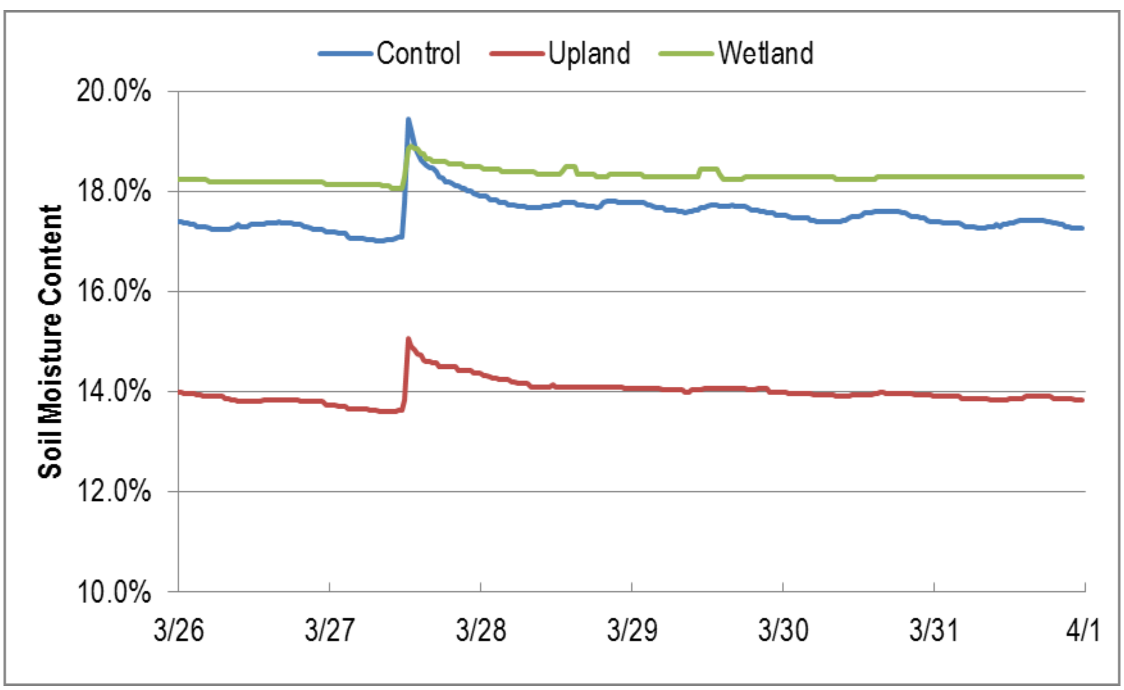

Figure 3. Typical soil moisture response to simulated storm event occurring March 27th

Overall, the Upland garden exhibited lower volumetric soil moisture content throughout the year of study when compared to the Control and Wetland gardens. The first four months of 2012 demonstrate strong soil moisture responses to simulated stormwater runoff events. Following the simulated event, the garden returns to prepulse soil moisture content within three to four days. The soil moisture content of the Upland garden drops by about 5% between May 1st and June 10th, and remained low for the rest of the summer. During the dry period between mid-May and mid-October, the wetting response of the Upland garden to stormwater pulses occurring during this period was observed to be minimal. In late October the soil moisture content rises by 5% and sensors again were sensitive to simulated stormwater pulses.

The Wetland garden displays a decrease in soil moisture content between May 28th and June 15th. The decline of soil moisture content in the Wetland garden occurred later in the season than the decline observed in the Upland garden, but the soil dried more quickly. The soil moisture content of the Wetland garden increased periodically throughout the summer in response to irrigation.

The volumetric soil moisture content data from the unvegetated Control garden show strong wetting responses to simulated storm events through the spring, dry season, and fall. Between June 6th and August 9th, the soil moisture content fell gradually by 5%. Moisture content rises again following the August 9th storm event, and strongly corresponds to simulated stormwater pulses for the rest of the year.

Plant Abundance

Allometric relationships

The woody plant allometry that was developed for the four woody plants, *A. cana*, *C. ledifolius*, *A. utahensis*, and *S. exigua*, all show strong regression relationships. The power function regression was chosen for its improved r^2 value and y-intercept compared to a linear fit, and it better represents the curve associated with natural plant growth (Figure 4). These regression equations were used to nondestructively scale the whole plant leaf area of each woody species from May through October in order to calculate the DTV from each species.

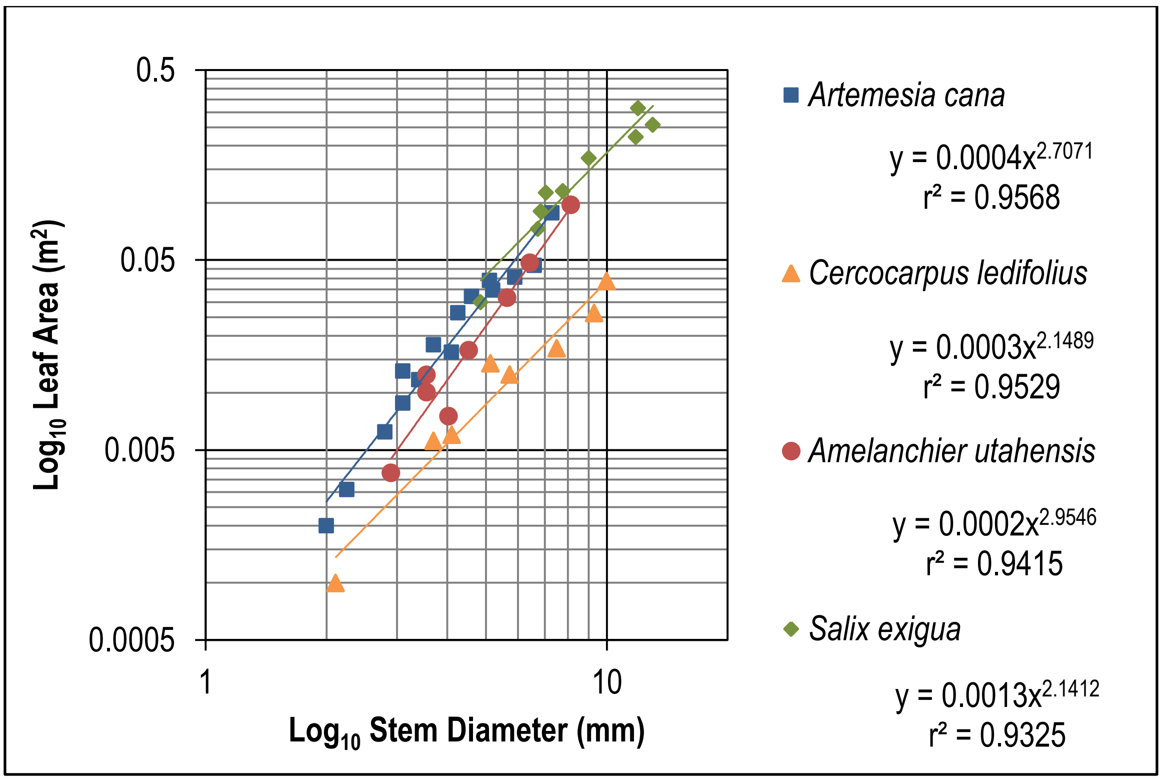

Figure 4. Stem diameter to leaf area regression equations

Upland garden

In the Upland bioretention garden, the plants demonstrated a relatively consistent growth pattern throughout the growing season. The *A. cana* individual had fully leafed out prior to May, but the *C. ledifolius* and *A. utahensis* demonstrated modest growth throughout the summer months. *A. cana* dominated the garden before it senesced in October (Figure 5). Like the *A. cana*, the *A. utahensis* was observed to senesce between September and October. The *C. ledifolius*—an evergreen plant—kept its leaves and became the dominant species in the Upland community in October. However, the *C. ledifolius* was vulnerable to predation and some damage due to mule deer herbivory was observed in November and December.

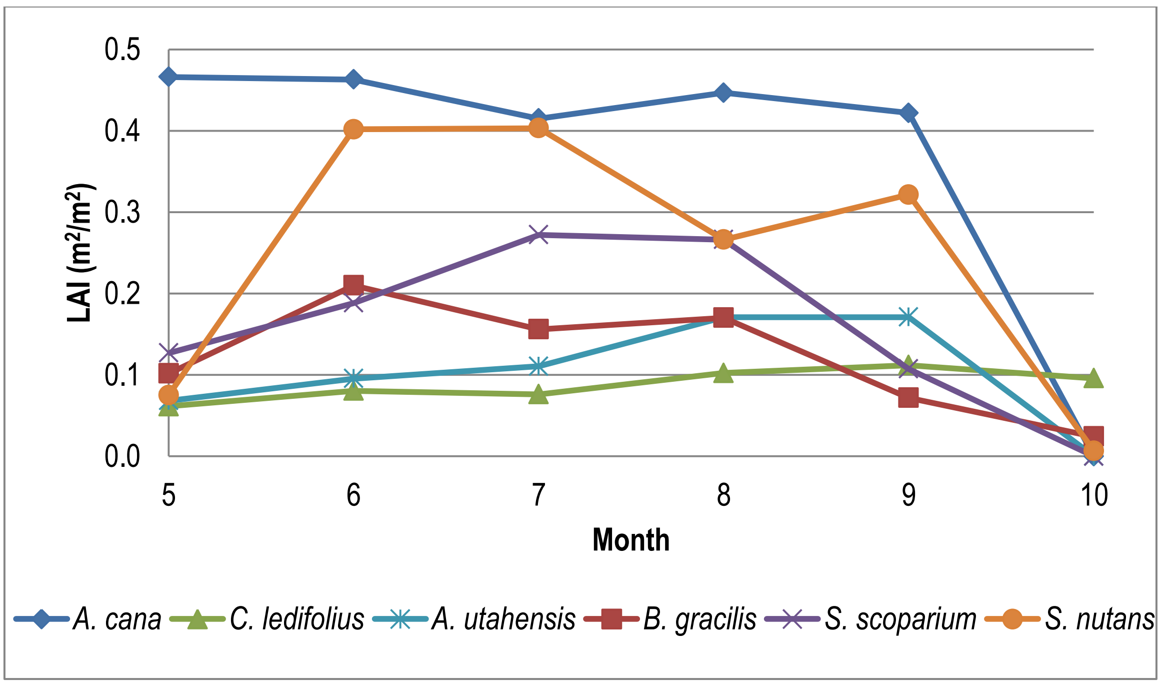

Figure 5. LAI for the Upland plant species from May to October.

Although planted (as shown in Figure 1), gas exchange and leaf area measurements were not performed on the *A. tridentata* individuals in the Upland garden. These individuals died prior to the start of the gas exchange measurement period. This was unexpected because these plants typically thrive in cold desert climates and were selected specifically for their prominence in Great Basin intermountain valley communities.

The perennial grasses of the Upland garden initially represented a low LAI. In June and July *S. nutans* was the dominant grass and demonstrates two clear growing periods, the first in early spring, and the second in early fall. *S. scoparium* showed an increase in LAI between May and July before it leveled off in August and declined through October, a pattern consistent with warm weather grasses. *B. gracilis* had a May and June growing season before it began to decline through October. Neither the *B. gracilis* nor the *S. scoparium* demonstrated dual growing seasons similar to the *S. nutans*. Figure 5 displays the changes in LAI for all six species in the Upland garden throughout the growing season.

Wetland garden

The leaf area in Wetland community was dominated by the *S. exigua* and *D. glomerata* for the entire growing season. These species showed resistance to fluctuations in simulated storm volume and frequency, and even demonstrated resilience to the interruption in irrigation described in the methods section. This behavior was expected because these species are typically found in nonhydric riparian soils, or just up moisture gradient of the obligate wetland species. Notably, the populations of species that require highly saturated soils throughout the growing season, such as the *Typha sp.* and

Phragmites sp., were reduced during times of reduced soil moisture. Figure 6 shows the changes in LAI of the five wetland species throughout the growing season as a ratio of total leaf area per species to the total area of the bioretention plot.

Transpiration Rate

Transpiration rates were observed to increase in the days following simulated stormwater pulses for each gas exchange sampling period with the exception of the June event. In most cases, the plants in both vegetated gardens were observed to respond to the simulated runoff pulse by increasing their peak daily transpiration rate on Day 3, and then returning to a lower value on Day 5 (see Table 4 for gas exchange schedule). However, the Upland garden displayed some variations on this trend, and both vegetated gardens demonstrate a marked deviation from this trend in June.

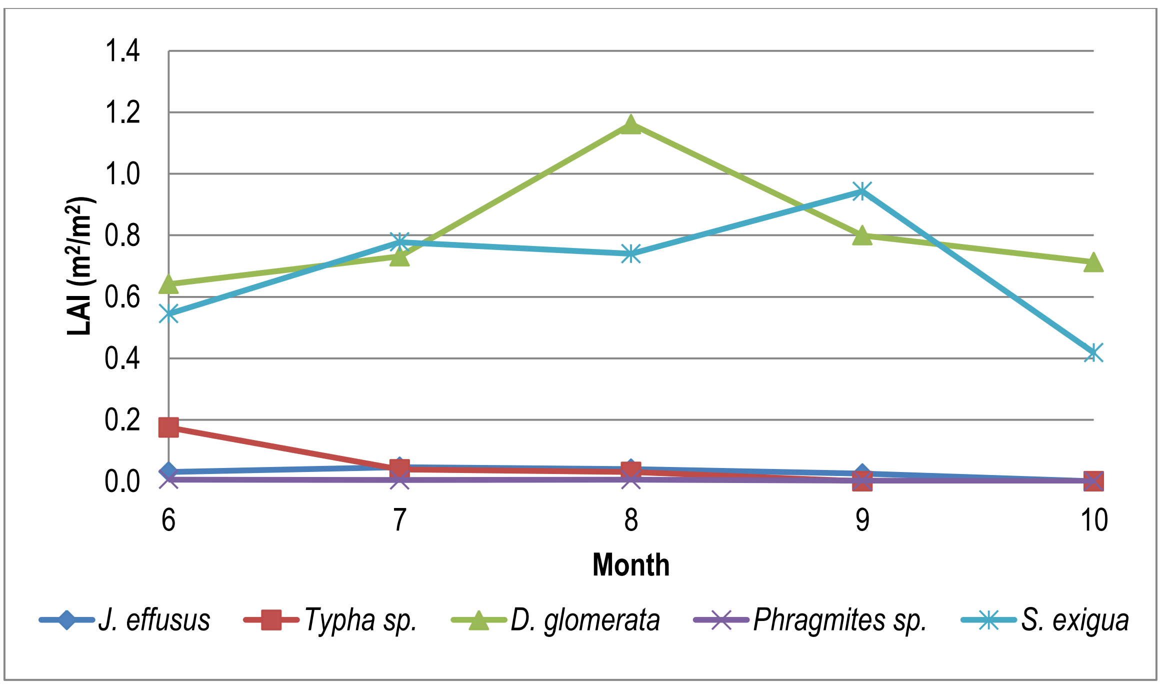

Figure 6. LAI for the Wetland plant species from June to October.

In the Upland garden, both the shrubs and bunchgrasses responded distinctively depending on the time of year and simulated runoff volume. In July, the only plant to respond appreciably to the small 100 L storm pulse during the period of measurement was the *A. cana*, whose peak transpiration rate increased from 3.5 on Day 1, to 4.1 on Day 3, and further to 7.1 mmol H_2O m^2 s^{-1} by Day 5. Sustained positive responses to simulated runoff pulses were also observed in the Upland garden during the month of August to a larger simulated event volume of 1515 L. Following this runoff pulse, both the shrubs and grasses increased their daily maximum transpiration rate throughout the period of gas exchange measurements, but the timing of the response was slightly different. The greatest increase of the shrubs occurred between Days 1 and 3 of the measurement series. For the grasses, the greatest increase in transpiration rate occurs between Days 3 and 5.

The Wetland garden transpiration response was less varied than the Upland responses. The Wetland did not show distinctive response trends associated with storm volume nor did they vary strongly month to month. The Wetland typically responded to runoff pulses quickly, and generally peaked on Day 3. This trend is illustrated in Appendix B: Transpiration Rate Figures, and in the following section on daily transpired volume.

Both gardens display a new trend in response to the June storm event. In June the transpiration rates actually fell following the stormwater pulse in both the Upland and the Wetland gardens. However, this reduction coincided with a low-pressure weather system that caused a 15 °C reduction of midday temperature and a 40% increase in relative humidity. In this case, the increase in available soil water did not cause an increase of transpiration rate in either vegetated garden.

Notably, on Day 1 of the June gas exchange series, transpiration rates for many of the species in the Upland garden were at their highest value observed throughout this study. Two plants in particular were especially high; the *A. utahensis*, and *C. ledifolius* had peak transpiration rates of 18.5 and 23.7 mmol H_2O m^{-1} s^{-1}, respectively. The atmospheric conditions on June Day 1 were 33 °C, vapor pressure deficit was 4.7 kPa, and relative humidity was 6%. Both of these conditions tend to create high transpiration rates when soil water is available. The dramatic changes to atmospheric conditions on Day 2 caused similarly dramatic reductions in transpiration rate.

The changes in atmospheric condition through the June gas exchange series reduced the transpiration rate of the wetland species as well, but the changes were of smaller magnitude. All gas exchange values from each species in the Upland and Wetland gardens May, June, July, August, and October are shown in Appendix B: Transpiration Rate Figures.

Transpired Volume

Daily transpired volume (DTV) from both the Upland and Wetland gardens indicated that vegetation was contributing to runoff volume reduction. Values for daily transpired volume were calculated using both the rate at which each plant was transpiring and the leaf area present in the garden. The plots showing measured and estimated values for DTV for each of the gas exchange sampling series can be found in Appendix C: Daily Transpired Volume.

In May, every plant species in the Upland garden shows an increase in DTV on the day following the simulated stormwater pulse. This response varies from a 46% increase for the *A. utahensis* to a 124% increase for the *A. cana*. The total DTV from the Upland garden increased by 103% on the day following the stormwater pulse, from 17.8 to 36.2 L. There was no estimate for Wetland garden DTV in May because leaf area data were not collected in this month and thus transpiration rate measurement data cannot be scaled.

Due to the atmospheric changes occurring in June, the DTV of the Upland garden was reduced by more than half from Day 1 to Day 3 as it fell from 90 to 43 L. Each of the plant species in the Upland garden reduced its DTV between 47% and 63%. The changes to the Wetland garden were similar, and its estimated DTV fell from 68 to 40 L.

The overall DTV response of the Upland garden to the 100 L July stormwater pulse was small in magnitude, but this response varied widely by species. In the day following the event, *A. cana* had the greatest increase in DTV of all Upland garden species, from 8 L on Day 1 to 12 L on Day 3 (+45%). *S. nutans* also increased DTV on the day following the event from 8 to 10 L (+16%). However, the DTV of two species actually decreased between Day 1 and Day 3; *C. ledifolius* decreased from 6.8 to 5.6 L (-17%) and *B. gracilis* decreased from 7.3 to 6.7 L (-9%). On Day 5, the *C. ledifolius* had reduced its DTV to 4.8 L (-30% from its prestorm value). Similarly, *A. utahensis* decreased its DTV from 5.5 L to 4.7 L (-15%) between Day 1 and Day 5. Conversely, the third shrub species, *A. cana,* increased its DTV from 8.3 to 17 L between Day 1 and Day 5. The net decrease in DTV for the *C. ledifolius* and *A. utahensis* over the five days of monitoring may be an indicator of water stress in these plants.

All of the plants in the Upland garden increase their DTV in the days following the August stormwater pulse; however, the response of the shrubs was markedly different from the response of the grasses. On the day following the simulated storm event the shrubs increased their combined DTV from 16 L to 24 L (+50%), while the grasses increased their combined DTV from 5.4 L to 13 L (+150%). On Day 5, the shrubs had increased to 26 L (+63% relative to Day 1), and the grasses had increased to more than 22 L (+300% relative to Day 1). In total, the DTV of the Upland garden had increased from 22 L on Day 1 to 49 L on Day 5, an increase of 124% The Wetland garden responded positively to the storm event as well, but since the DTV estimates were already quite high, the changes were less dramatic than for the Upland garden.

In October many of the plants in the Upland garden had senesced, and the ones that remained (except for the evergreen *C. ledifolius*) were in the process, and the plot DTV was low, ranging from 2.2 to 3.5 L. Though the DTV was quite low, all three species responded to the stormwater pulse with more than a 20% increase in daily transpired volume on Day 3, but by Day 5 the total volume transpired changed by -26% compared to Day 1 (Appendix C: Daily Transpired Volume). Similarly, the Wetland garden showed a DTV increase on Day 3, but a net decrease between Day 1 and Day 5.

Bioretention Garden Outflow and ET Reduction

The percent of water leaving each of the three gardens varied both by vegetation type and by season. All three gardens followed a similar trend from January to March, but the vegetated gardens began retaining more water than the unvegetated Control in April. The July storm volume was so small that all three gardens were able to retain its full volume.

Following July, the region's driest month, all three gardens performed similarly. Each gradually increased the total monthly outflow volume as storm frequency and runoff volume increase through autumn and winter. Figure 7 shows the annual monthly water balance of all three bioretention cells. The outflow volume represents runoff that would have infiltrated, not volume delivered to downstream stormwater infrastructure and receiving waters. The gravel storage layer was sized specifically to hold the runoff volume of the largest average event, and the underdrain was throttled to approximate a 1.5 cm/hr infiltration rate. The gardens were sized such that there would be no discharge to stormwater infrastructure for 95% of annual rainfall events. During the monitoring period, no storm volumes were simulated that would have caused discharge into downstream stormwater infrastructure systems.

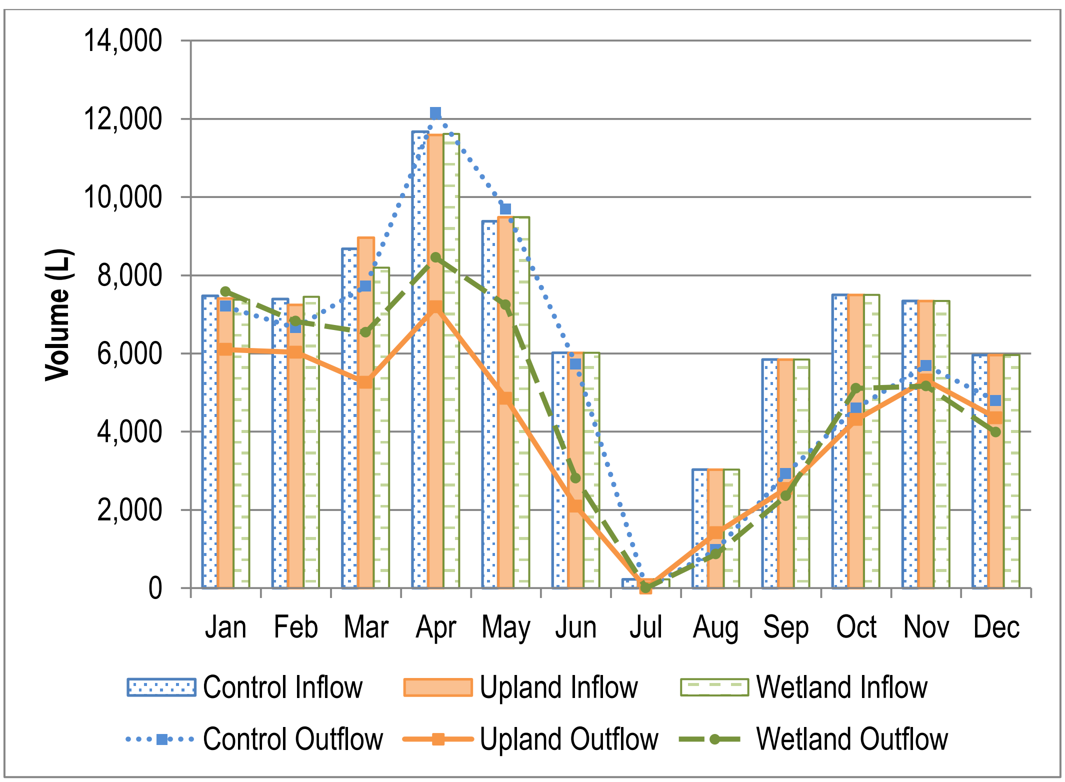

Figure 7. Average monthly water balance from the Control, Upland, and Wetland gardens.

Periodic difficulties with the tipping bucket instrumentation, including freezing of the tipping bucket, freezing and breaking of the pipe, and other site disturbances, resulted in an undetermined volume drained from the garden. In total, 31 of 49 annual runoff events had a recorded outflow volume for the Control garden, 38 events were recorded from the Upland, and 36 from the Wetland. Appendix D: Storm Data Used for Analysis contains data regarding the actual annual volume administered and outflow volume measured for this study. Because of these data gaps, the outflow values used to create the annual budget shown in Figure 7 were determined using monthly average outflow volume and scaling by the number of storms that were simulated. The inflow values were simply the sum of each simulated stormwater runoff event that occurred in that month.

The annual runoff reduction attributable to ET for each garden was computed using the storm volume administered and the volume drained. The difference between these values was considered to be held by the garden soil media, and ultimately either transpired or evaporated. The total volume reduction attributed to the processes of ET from each garden was assumed to be the total annual volume *not* drained from each garden. This assumes that the annual change in storage volume was negligible; in fact the total storage capacity of the garden was 2700 L, or only 3.3% of the total inflow volume over the year of study.

The annual ET reduction calculated was 18% for the Control garden and 37% for the Upland garden. The Wetland garden ET reduction was 28%, but was calculated using only the storm volume administered and storm volume drained. This value does not include irrigation because the irrigation outflow could not be reliably measured using the current tipping bucket instrumentation.

A summary of all directly measured values of the water balance of each garden is shown in Table 5. This table displays average inflow, average outflow and estimated transpiration volume for single runoff events occurring in each month. Transpiration in the Upland garden was shown to reduce runoff inflows by 10 to 20% of most summer runoff events, and for small events in July the runoff reduction is even greater. The Wetland garden was observed to transpire a considerable fraction of runoff inflow volume in August, near 60%. All three bioretention gardens appear to be performing similarly during the last five months of the year as shown by the IV:RO values in this period. This pattern is also shown graphically in Figure 7.

Table 5. Summary of measured single runoff event data showing the average values for runoff volume and infiltrated volume for a single storm in each month. The estimated one-week transpired volume is also shown.

Garden		Month											
Control		**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
	RO[a] (L)	1495	1478	1752	1946	1875	2006	114	1514	1949	1874	1836	1192
	IV[b] (L)	1440	1331	1414	2026	1735	1908	0	490	977	1150	1422	957
	TV[c] (L)	0	0	0	0	0	0	0	0	0	0	0	0
	IV:RO	0.96	0.91	0.81	1.04	0.93	0.95	0.00	0.32	0.50	0.61	0.77	0.80
	TV:RO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Upland													
	RO[a] (L)	1481	1449	1793	1932	1897	2006	114	1514	1949	1874	1836	1192
	IV[b] (L)	1220	1206	1051	1198	970	697	0	707	848	1078	1330	871
	TV[c] (L)	0	0	0	N/C[d]	167	421	351	280	N/C	19	0	0
	IV:RO	0.82	0.83	0.59	0.62	0.51	0.35	0.00	0.47	0.44	0.58	0.72	0.73
	TV:RO	0.00	0.00	0.00	N/C	0.09	0.21	3.09	0.18	N/C	0.01	0.00	0.00
Wetland													
	RO[a] (L)	1475	1490	1639	1935	1896	2006	114	1514	1949	1874	1836	1192
	IV[b] (L)	1515	1364	1308	1408	1447	935	0	434	786	1277	1291	796
	TV[c] (L)	0	0	0	0	N/C	430	678	901	N/C	148	0	0
	IV:RO	1.03	0.92	0.80	0.73	0.76	0.47	0.00	0.29	0.40	0.68	0.70	0.67
	TV:RO	0.00	0.00	0.00	0.00	N/C	0.21	5.97	0.59	N/C	0.08	0.00	0.00

Notes: [a]RO = average monthly storm runoff volume delivered to bioretention garden
[b]IV = average monthly volume leaving garden via underdrain; represents infiltration
[c]TV = estimated one-week transpired volume
[d]N/C = value is not zero and is not computed or estimated in this study

DISCUSSION

Synthetic Storms and Irrigation

Field observations indicated that each of the three garden types proved capable of containing and draining all of the simulated runoff over the year of monitoring, and surface ponding was not observed to persist longer than the simulated event duration. This indicated that the gardens were able to effectively channel simulated runoff inflow into the storage layer to help create well-drained conditions for the soil media.

The Upland garden plants required no supplemental irrigation, but did demonstrate seasonal responses to fluctuating water availability. The relative drought of July and August resulted in late summer senescence of the grass species. However, these grasses displayed strong regreening responses to runoff inputs during these periods that were indicative of their resilience to water scarcity. The deeply rooted shrubs also demonstrated drought tolerance by maintaining leaf area through the driest months and continuing to transpire water. All of the plants in the Upland garden demonstrated resilience to summer dry periods without irrigation.

The irrigation delivered to the Wetland garden proved inadequate to support the *Typha sp.* and most of them had senesced by August as shown in Figure 6. In general, the plants that dominated the Wetland garden were not obligate wetland species (indicative of under watering). Both the *S. exigua* and *D. glomerata*, plants that prefer well drained soils that receive lots of water, did extremely well in the Wetland garden and did not senesce until autumn.

Soil Moisture

The volumetric soil moisture data responded to stormwater pulses as expected during the first four months of 2012 for all three gardens. The combination of high storm event frequency and high storm volume resulted in the soil moisture data being highly responsive to each simulated stormwater pulse.

However, beginning in May the Upland garden began to deviate markedly from the pattern of stormwater pulse responses established over the previous four months. In May, the average volumetric soil moisture content of the Upland garden dropped precipitously in spite of being inundated with 9500 L of water over five storm events. Each simulated stormwater pulse caused a subtle bump in soil moisture content measured by the sensor, but overall, the response was not as pronounced as it was to storms in the previous four months and the soil slowly dried until June. The Upland garden remained at this low soil moisture content until late October before the sensors began to respond to stormwater pulses as they had during the winter and spring. Similarly, the Wetland garden demonstrated a steep decline in soil moisture in late May which occurred over just a few days. The sensors in both vegetated gardens reached their annual minimum at this time of year.

The cause of the soil moisture reduction occurring in the vegetated gardens during May appears to be related to the increased water demand of the plants in the growing season. Notably, the Control garden experienced no decrease in soil moisture content until late June, and the rate of decrease was much less than that of the other two gardens. However, the sensors in the Upland garden remained less responsive to rewetting for a longer period than the sensors in either the Control or Wetland gardens.

The insensitivity of the sensors in the Upland garden to stormwater pulses between June and October was most likely attributable to localized soil conductivity reductions caused by several factors, including the ET demand of the growing season. Soil moisture and conductivity can be extremely heterogeneous, even in plots as small as the ones in this study. Other researchers have observed highly localized effects on soil moisture content and hydraulic conductivity as a result of vegetative cover and subsurface irregularities (Atchley and Maxwell, 2011). The soil moisture sensors were located at the center of the garden, and were situated in close proximity to an *S. scoparium* and two *B. gracilis* plants. The water demand of these plants caused a localized reduction in soil conductivity and thus negatively affected the rewetting ability of the soil column that surrounded the sensors.

The design of the garden may have also played a role in creating conditions leading to the reduced soil conductivity and dampened the sensitivity of the sensors to simulated runoff events. Both the Upland and Control gardens employed a gravel forebay, which intercepted stormwater inflow and conveyed it directly to the gravel storage layer beneath the topsoil. The garden was also lined with a 40 mil PVC liner. One or both of these design factors could have provided a pathway into storage that offered less resistance than wetting the vertical soil profile. In addition, the gravel storage layer of the garden was drained at the bottom within a couple of days following the runoff pulse to simulate infiltration. Native soils receiving the infiltrated garden effluent would naturally reach a saturation point and cause residence times in the garden longer than those simulated for this study. If these design factors caused the reduction in soil moisture, the effects would likely have been most pronounced at the center of the garden, the location of the sensors.

In general, reduced soil conductivity is an undesirable performance characteristic of bioretention systems because it increases surface ponding, reduces overall holding capacity, and restricts the runoff contact with the soils and roots that are necessary for biogeochemical processes to remediate pollutant loading. Future semiarid system designs should take this possibility into account by incorporating designs that prevent reductions in soil conductivity. Bioretention systems are meant to optimize the vertical movement of water through the soil media to improve the hydrologic performance by restoring infiltration and transpiration water pathways, and to improve water quality by increased contact time with soil particles, microbes, and plants. A bioretention system with low soil conductivity is less effective at achieving hydrologic and stormwater quality goals.

Plant Abundance

The method for estimating leaf area in the Upland garden yields an area computed several days following the stormwater pulse and therefore cannot capture the regreening ability of this system. The rapid growth in direct response to stormwater pulses is illustrated in the images in Figure 8 that were taken in the Upland garden both before and after the storm event that occurred on September 9th. This regreening effect was also observed during the August storm events.

These images show the importance of mixed communities in Upland gardens. Although the bulk of the transpiration was done by the shrubs, roughly 57% of the total annual transpired volume, the grasses’ response to stormwater pulses during the driest

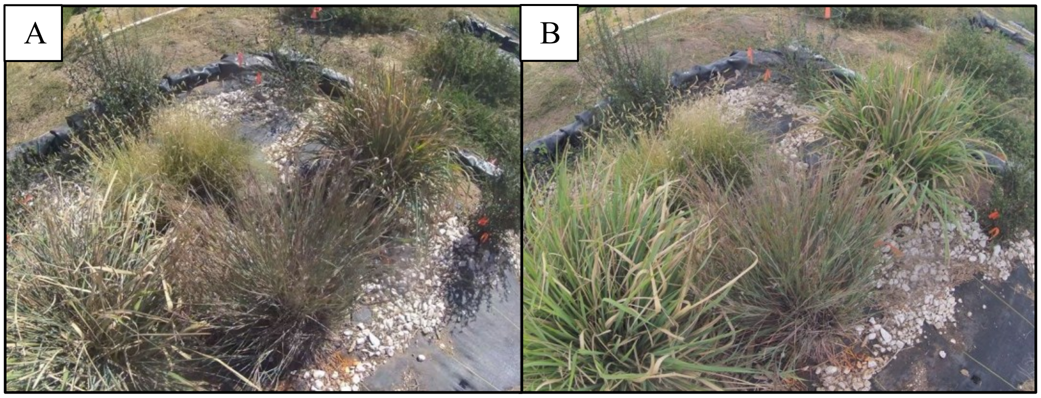

Figure 8. Regreening response of regionally native vegetation. A) Upland grasses before storm pulse. B) Upland grasses 24 hours after stormwater pulse. Images captured in September.

months was more pronounced. Rapid responses enable the system to transpire more storm runoff volume more quickly, which helps the site meet its goal of restoring more natural hydrologic function. System regreening also indicates increased metabolic rate in the plants, especially the grasses. Future studies might try to determine if there is a nutrient removal advantage pursuant to the rapid plant growth and accompanying nutrient uptake.

Not all plants responded positively to stormwater pulses. The *Artemisia tridentata* plants that were part of the original Upland community design survived for only two years and had completely died before this study began. This plant is a well-studied and famous member of cold desert communities and was selected for this study because it is commonly planted in nonirrigated xeriscaping efforts throughout the American West. However, this plant species does not do well in soils that are saturated or anaerobic for more than a couple of days (Barbour and Billings, 1999). Since this bioretention design includes several features to improve soil drainage (forebay, storage layer, underdrain) it was not anticipated that the runoff events would negatively affect these plants.

Unfortunately, this was incorrect and the frequency of simulated runoff inundation caused soil conditions that proved fatal for the *A. tridentata.* Notably, the *A. cana* plant, which is known to be better adapted to udic (poorly drained) soils, thrived in the Upland bioretention garden, and is a recommended alternative to *A. tridentata* in future semiarid bioretention systems (Barbour and Billings, 1999).

Transpiration Rate and DTV

In general, transpiration rates were higher than expected, but especially on June 4th, the first day of June measurements. The transpiration rate of the *C. ledifolius* and *A. utahensis* were uncharacteristically high on this day, This could be due to bias in the instrument as it gets hot during data collection and creates conditions within the gas exchange chamber that were warmer than the ambient air, and perhaps creating an artificially high transpiration rate. In fact, for both of these plants, the maximum recorded transpiration rate of the entire growing season occurred on June 4th. However, the measurements made on the Wetland plants occurred under similar cuvette conditions, relative maxima were not observed for any of the wetland plants.

Plants adapted to semiarid climates have been shown to have high transpiration rates when water is abundant and vapor pressure deficit is high. Under certain conditions, stomatal regulation during times of water abundance is not a high priority for plants that are adapted for dry climates, and conductance may remain high. Plants adapted for water scarcity may prioritize CO_2 assimilation and more rapid nutrient uptake ahead of water conservation if water is abundant. Others have observed semiarid adapted shrubs transpire at similarly high rates, for example, *A. tridentata* was observed to achieve transpiration rates in the field in excess of 18 mmol m^{-2} s^{-1} by Kolb and Sperry (1999).

However, most existing research that measures leaf level transpiration is done on plant communities coupled with natural hydrologic conditions; very little data exist for semiarid plants functioning under highly modified hydrologic conditions.

In this study, these hydrologic modifications were extensive. The natural precipitation depth in this climate is roughly 37 cm per year, but because of the garden area to drainage area ratio (GA:DA), the precipitation delivered represents over 800 cm of depth per year. This change in hydrologic regime may account for some of the unexpected behavior observed in this study, including high transpiration rates.

The plants in the Upland garden took advantage of this water in different ways. For example, the response to the August storm event varied between the shrubs and grasses. This simulated runoff event in August was large (~1500 L), and happened right after the driest month of the year. All of the Upland plants responded by increasing their transpiration rates on the day following the runoff pulse, but the grasses continued to increase their transpiration rate even after the shrub transpiration rate had decreased. The grass species were quite dry when the gas exchange measurement period began, indicating some drought induced senescence. But the rapid regreening response (similar to that shown in Figure 8), heightened transpiration rate, and DTV increase made over the five days of gas exchange measurements demonstrated how flexible the grasses in this plant community can be during times of water limitation.

As expected, the estimated DTV values also seem high for each sampling series, June in particular. This bias was caused by the methods of measurement and scaling that yield theoretical maximums rather than actual volume transpired. These values do not account for in situ variables including light/temperature reduction due to self-shading and leaf angle, turbulence effects of the plant canopy's boundary layer, or growth resulting during the period of gas exchange measurement (substantial in August) from increased water availability. There was also potential error that was unaccounted for due to the allometric relationships used to scale the leaf area of woody plants. This value was therefore an approximate maximum value for daily transpired volume.

However, accepting these values as theoretical maximums, we can estimate how much volume each system transpired during the growing season. These estimates assume that the period of measurement was representative for the entire month in which the measurements were taken, and uses the weekly values shown in Appendix C: Daily Transpired Volume to approximate an annual maximum transpiration volume.

For the Upland garden we find that the plants transpired up to 5600 L of the inflow volume during the growing season, roughly 7% of the total yearly runoff volume. Similar estimates for the Wetland garden yield roughly 12,000 L of transpired volume (120 cm), or 15% of the total yearly runoff volume (13% of total inflow volume including irrigation). This calculation indicates that the Wetland garden may have transpired roughly double the volume of the Upland community (perhaps more since not every species in the Wetland was measured for this study), but the additional transpiration came at the cost of irrigation demand. Roughly 11,700 L of water were required to maintain the Wetland community, and based on the loss of certain obligate wetland species the irrigation delivered may not have been enough.

Though the Wetland garden might more closely restore the hydrologic pathway of ET to an urbanized site to predevelopment conditions, the maintenance and environmental costs associated with irrigation in desert climates may not balance the benefit of slightly more transpired volume.

Bioretention Garden Outflow and ET Reduction

Since each bioretention system was lined, the difference between inflow and outflow must have left the system from the garden surface, either by evaporating directly, or being transpired through the plants. However, this calculation suggests that the Upland garden lost 39% of its annual inflow to ET. This high ET percentage is unlikely for cold desert climates because the majority of precipitation occurs between October and April, during which the potential for ET is low. It was more likely that there was a tear in the Upland garden's liner, through which simulated runoff volume escaped and was missed by the tipping bucket instrumentation at the underdrain. During an accidental irrigation pipe breakage in June that saturated the ground surrounding the three bioretention gardens, the Upland garden was observed draining water from the underdrain pipe, indicating that water from the surrounding saturated soils was percolating into the garden through the PVC liner where it then flowed out the underdrain. If water could flow from surrounding soils into the Upland garden, then simulated runoff volume could be lost as well. It is difficult to determine if a tear in the PVC liner exists without digging up the garden. Continued monitoring of the Upland garden tipping bucket data will help illuminate the cause of the missing volume from the tipping bucket records.

ET estimations for the Control and Wetland garden were more reasonable: 15% and 29%, respectively. The Wetland ET estimate does not include irrigation inflows because tipping bucket data between runoff pulse events were deemed more error-prone because tips occur at irregular intervals, which decreased confidence for these sections of the data record. The 29% ET value was the percent of annual stormwater runoff that was reduced due to ET. The annual ET percent lost from the Control garden offers an approximate value for just the evaporation component of ET.

By combining the evaporation estimate from the Control with the maximum transpiration estimate from the Upland, we compute an upper limit of 22% of the inflow volume leaves the Upland garden by ET. This is important when considering the legal implications of LID in desert communities. Many western states allocate water based on some form of prior appropriations water right law. If bioretention systems are using more water than the natural hydrology of a site can offer, the runoff may be considered to be put to beneficial use, and therefore require acquisition of a water right. The results of this study indicate that the use of bioretention systems in cold desert semiarid climates will likely not interfere with downstream water rights because the upper limit on ET is only 22% of annual inflow.

CONCLUSIONS

The ET volume estimate from each 10 m^2 bioretention test garden was expected to be less than the ET from an undisturbed drainage area of 220 m^2 and greater than the ET from an undisturbed area of 10 m^2. A semiarid desert site is expected to lose 10 to 30% of annual precipitation volume to ET (MacMahon, 2000; West and Young, 2000). The results of this experiment suggest that the ET performance of the Upland bioretention garden is likely unable to completely restore an urbanized drainage area back to undisturbed hydrology, but the garden loses more inflow to ET than is expected for an undisturbed site of equivalent area. The Upland garden was shown to lose a maximum of 22% of the runoff inflow to ET, a value that is less than the maximum ET from an undisturbed drainage area, but of greater volume than that from an undisturbed area of equal size as the garden.

The vegetation in the Wetland garden was expected to be less resilient to fluctuations in water availability than the vegetation of the Upland garden. This proved to be true as some late summer mortality was observed for both the *Typha sp.* and *Phragmites sp.* in the Wetland garden in spite of summer irrigation efforts. The Upland community had some late summer grass senescence, but strong regreening responses were observed when water became available. No irrigation was required to sustain the Upland community.

The gas exchange measurements were expected to demonstrate marked positive responses to runoff inflows in both of the vegetation gardens. This study found that the transpiration rates of vegetation in bioretention garden increased in response to simulated runoff events in most cases. In the Upland plant community, the transpiration response was shown to vary by runoff inflow magnitude (e.g., the small runoff volume in July resulted in small transpiration response), and varied by plant functional type (e.g., drought season grass senescence and subsequent regreening response to August and September runoff pulses). This study was unable to determine conclusively whether these differences in response were due to differential soil moisture utilization, or were due to the other morphological differences between grasses and shrubs. However, the sustained response of grasses to late summer runoff pulses was shown by both gas exchange measurements (August) and by garden observation (Figure 8) to be markedly different from the response of the shrubs, which did not demonstrate a regreening response that correlated to the runoff pulses.

The total ET volume leaving each garden was expected to increase according to vegetated cover type, with unvegetated Control having the lowest ET value (essentially only evaporation) and the Wetland having the highest ET value due to the high water demands of the vegetation. This study determined that the bioretention gardens followed this pattern, with the Control ET estimated to be 15%, the Upland ET estimated at 22%, and the Wetland ET estimated near 29%. Values for transpiration also varied according to this pattern, with the Control at 0%, Upland at 7%, and Wetland at 15%.

The advantage afforded by vegetation was shown to include improved runoff reduction per storm event throughout the year compared to the unvegetated system, and volume reductions attributable to evapotranspiration that more closely reflect the natural hydrology of an undisturbed site. The annual volume transpired by the plants in the

Upland garden was estimated to be small, roughly 7% of the annual inflow water volume. The reasons for this low value are twofold. First, the bulk of rainfall events, and thus runoff volume, occur opposite the growing season in cold deserts, during which time the runoff infiltrates in natural ecosystems. During periods of greatest opportunity for runoff volume reduction most semiarid adapted plants are dormant. Second, the garden area to drainage area ratio (GA:DA) for this study was only 4.5%. We expect that undisturbed semiarid adapted cold-desert ecosystems transpire less than 20% of annual rainfall, and for the rest to be infiltrated. In this engineered system, the bioretention garden plot received about 22 times the volume of water than would fall naturally on the plot in an average year, and was still able to transpire about 7% of that volume, though this transpired volume estimate is high because of the methods used to scale the leaf level gas exchange measurements.

Design Recommendations

If emulation of natural hydrology is the goal of future implementations of bioretention systems designed for semiarid climates using upland plants, consideration must be given to the strategic use of forebays, underdrains, and liners. Several of these bioretention design features may have been artificially introducing water stress on the plants in the vegetated systems, particularly the Upland garden. The combination of utilizing the lower underdrain to empty the storage layer, the PVC liner to ensure water balance, and the gravel forebay to promote storage, greatly reduced the responsiveness of the soil moisture sensors located in the center of the garden by reducing the hydraulic conductivity of the soil. This drier soil would have been more difficult for the grasses to absorb water from, and the rapidly draining storage layer may not have provided a reservoir on which the deeply rooted shrubs could rely between storm pulses. For native upland plant communities, the intent of a bioretention system design that employs a gravel storage layer and a forebay was to emulate what occurs naturally: precipitation runoff during the winter and spring is stored in shallow groundwater, which is available for uptake by the deeply rooted shrubs throughout the summer. Because this system had a forebay, a liner, and was drained at the bottom of the garden profile, the natural pattern of storage and availability was not accurately simulated. A system installed without a liner and with an overtopping control structure rather than an underdrain would likely be better equipped to emulate natural spring storage in shallow ground water.

Because of the combination of relatively small population of plants and the high inflows caused by the GA:DA ratio in engineered bioretention systems, reliance on plants for stormwater volume reduction is not recommended. However, runoff volume reductions are not the only benefit of including plants in bioretention design. In addition to the aesthetic benefits of vegetation, plant roots can improve vertical infiltration rates by creating macropores and vertical channels and also may improve the water quality by plant nutrient uptake, physical entrapment, and microbial activity, although more research on semiarid bioretention systems is needed to explore these possibilities further.

Future Work

Many aspects of bioretention in semiarid climates would benefit from further investigation, including increasing the vegetation density, adapting harvesting techniques, and variations of native plant community composition. Benefits of increased plant density could include improvements to both the potential transpiration volume and nutrient removal capacity of these systems. Examining homogeneous plant communities composed of either deeply rooted shrubs or bunchgrasses could yield improvements to vertical infiltration and transpiration performance or to nutrient removal or remediation. Developing an understanding of bioretention systems as engineered ecosystems could help these LID techniques meet site-specific hydrologic and water quality goals.

Future work is also needed to more finely determine the water balance of these systems. Utilizing weighing lysimeters to directly compute ET offers the advantage of highly reliable continuous data, but these systems are quite costly and may prove difficult to connect to a drainage (or water tank) in a way that approximates the periodic stormwater pulses of in situ bioretention systems. Large-scale gas exchange experiments that cover the entire garden with an air-tight tent are also technically possible, but matching the conditions in the tent to the ambient conditions outside is extremely difficult, e.g., replicating a stiff cool breeze or a naturally occurring precipitation event.

The most comprehensive way to assess bioretention performance in a semiarid climate is to install working systems that actually intercept stormwater runoff and infiltrate it into the soil. In situ bioretention monitoring studies that begin at small scales will require high levels of cooperation between the academic community designing and monitoring the site, and forward thinking stakeholders that need a vegetated landscaping feature and are interested in an experimental system design. In situ studies will be able to examine the actual chemical contents of local stormwater, the qualitative functionality of the bioretention system, and the response of different vegetation designs. This type of cooperation is underway to some degree at the University of Utah, but more work is needed to increase stakeholder involvement so that LID is not viewed as a costly liability but as a project element that adds value, aesthetics, and function to urban developments.

APPENDIX A

VOLUMETRIC SOIL MOISTURE CONTENT

This appendix contains quarterly figures showing the results of the continuous soil moisture monitoring for year 2012. Note the distinctive patterns of soil moisture increase that correspond to simulated storm runoff events. Also note the unresponsiveness of the Upland garden between June and October despite simulated storm runoff events occurring as scheduled in Table 3. In short, this unresponsiveness is due to a localized reduction of soil conductivity at the sensor site caused by the Upland garden vegetation. Full discussion and analysis can be found in the Discussion section of this thesis.

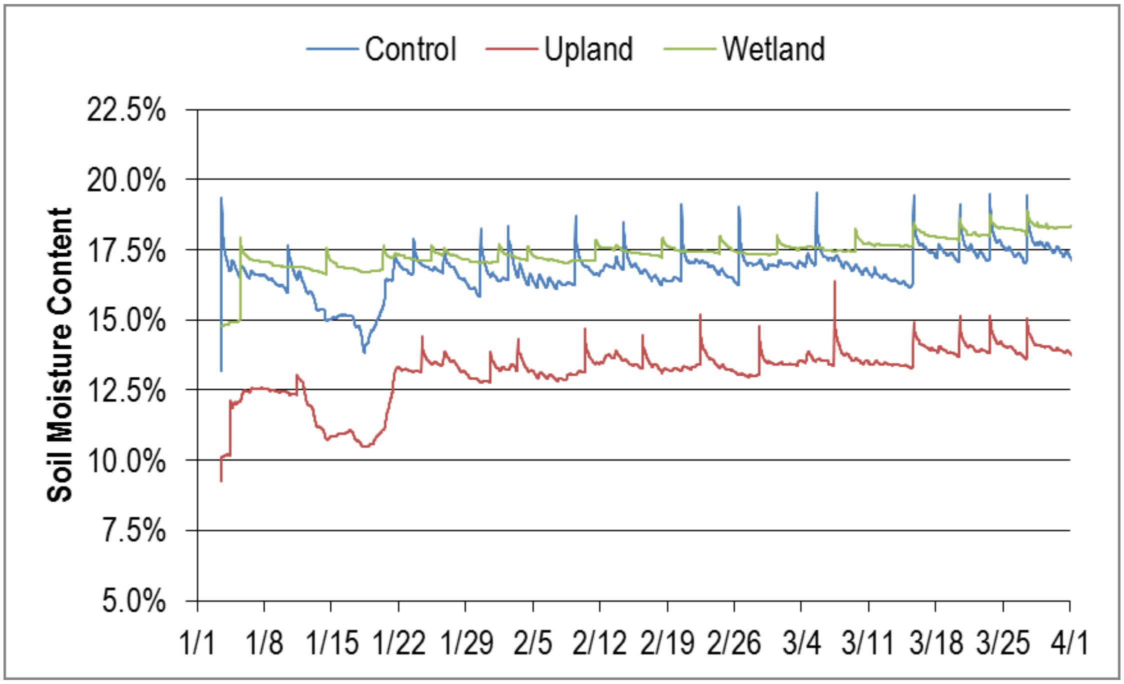

Figure 9. Volumetric soil moisture January through March

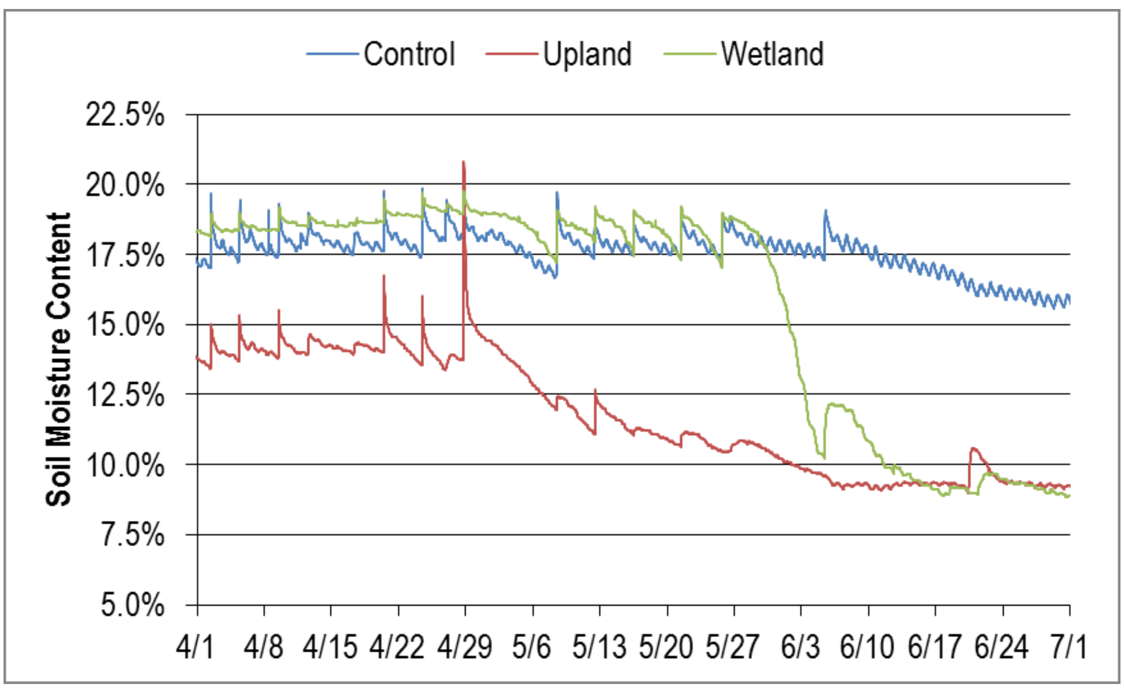

Figure 10. Volumetric soil moisture April through June

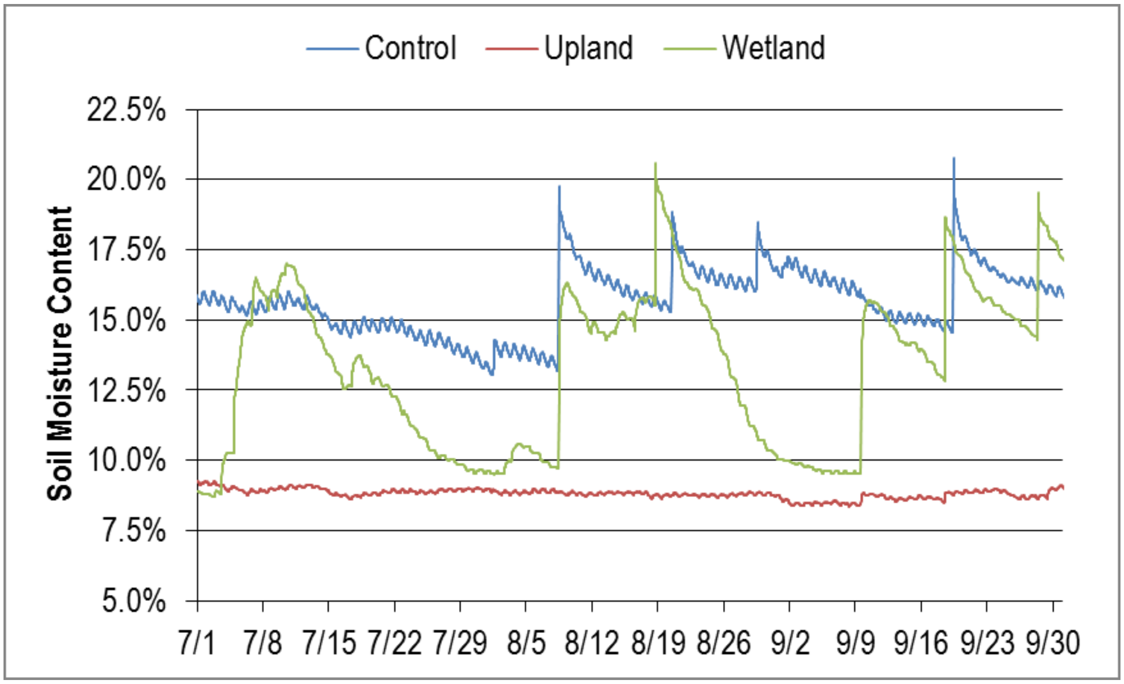

Figure 11. Volumetric soil moisture July through September

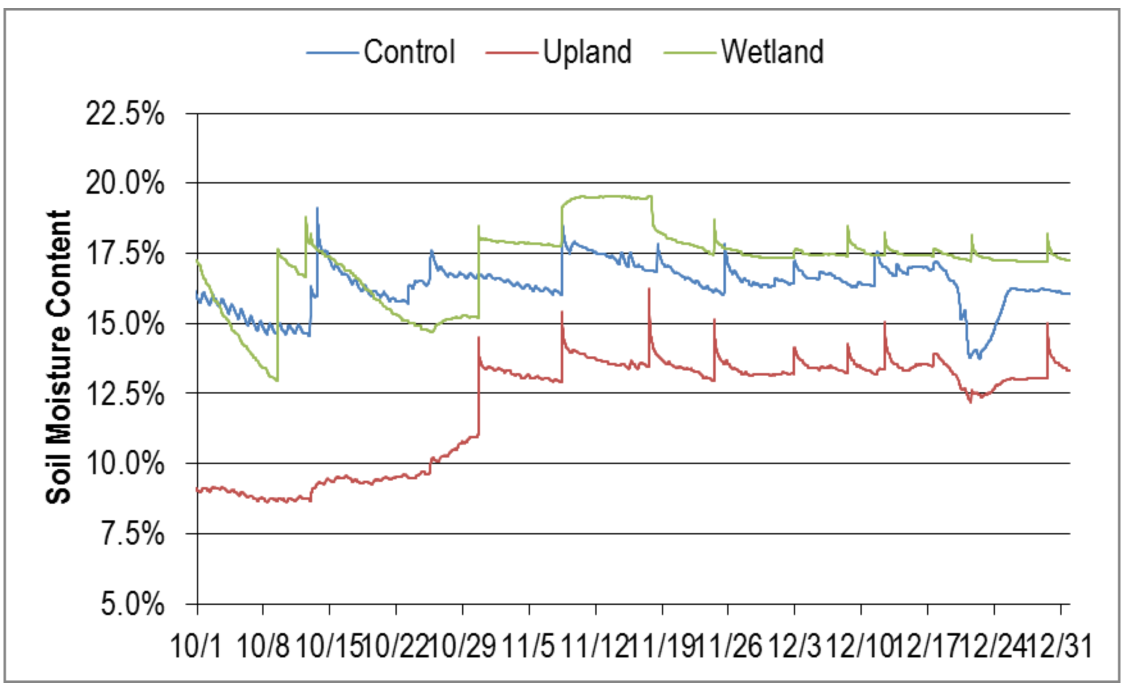

Figure 12. Volumetric soil moisture October through December

APPENDIX B

TRANSPIRATION RATE FIGURES

This appendix contains plots showing the transpiration rate response (*E*, mmol H_2O m^{-2} s^{-1}) for the months of May, June, July, August, and October. September was excluded from this study due to instrument maintenance.

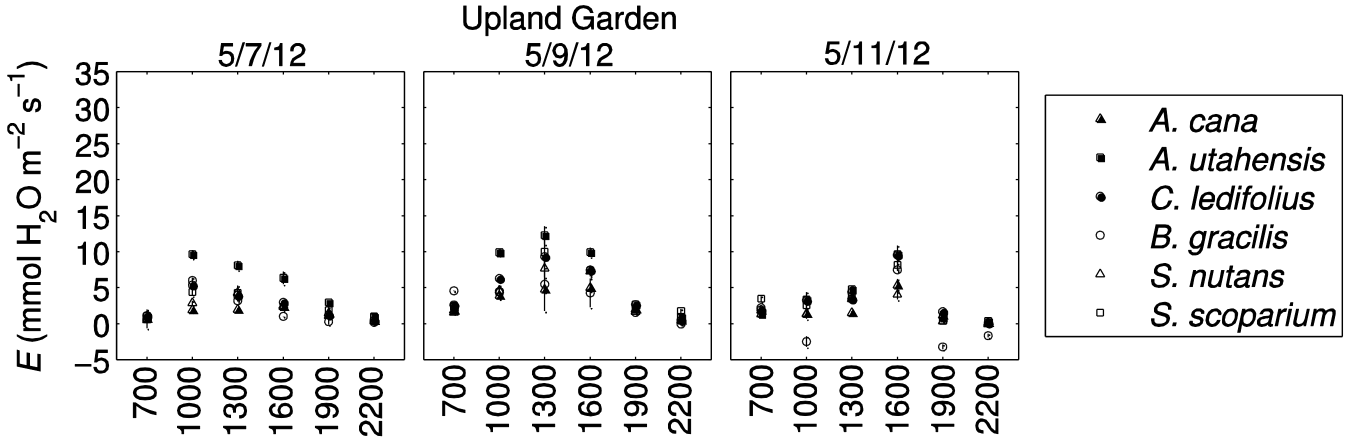

Figure 13. Transpiration rate (E mmol H_2O m^{-2} s^{-1}) for simulated Upland May storm occurring 5/8/12

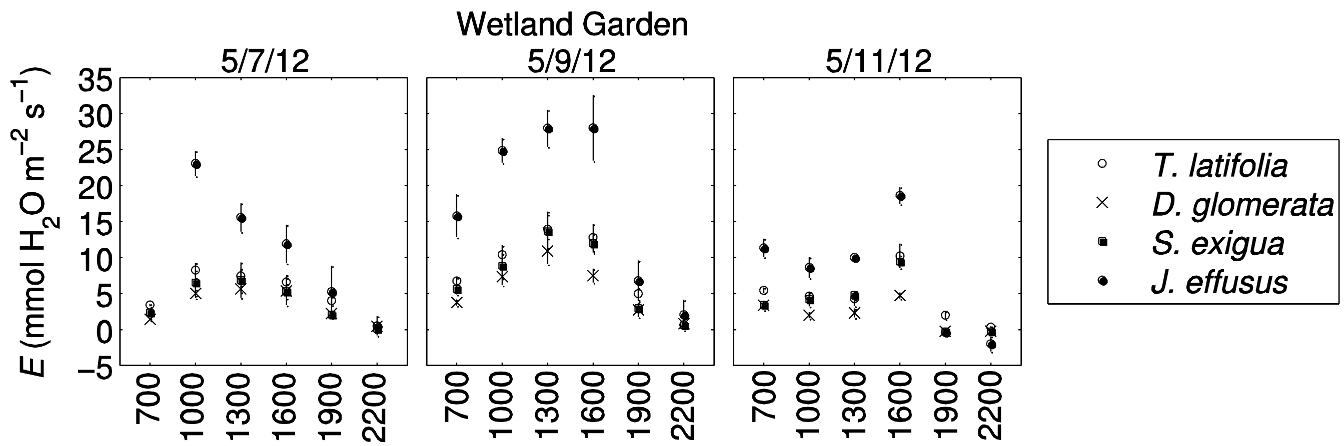

Figure 14. Transpiration rate (E mmol H_2O m^{-2} s^{-1}) for simulated Wetland May storm occurring 5/8/12

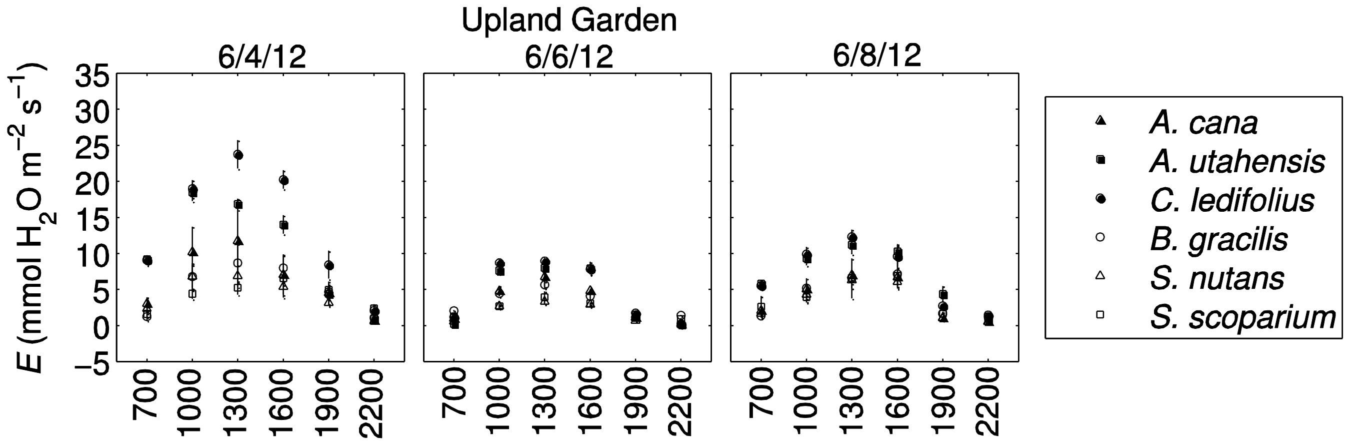

Figure 15. Transpiration rate (E mmol H_2O m^{-2} s^{-1}) for simulated Upland June storm occurring 6/5/12

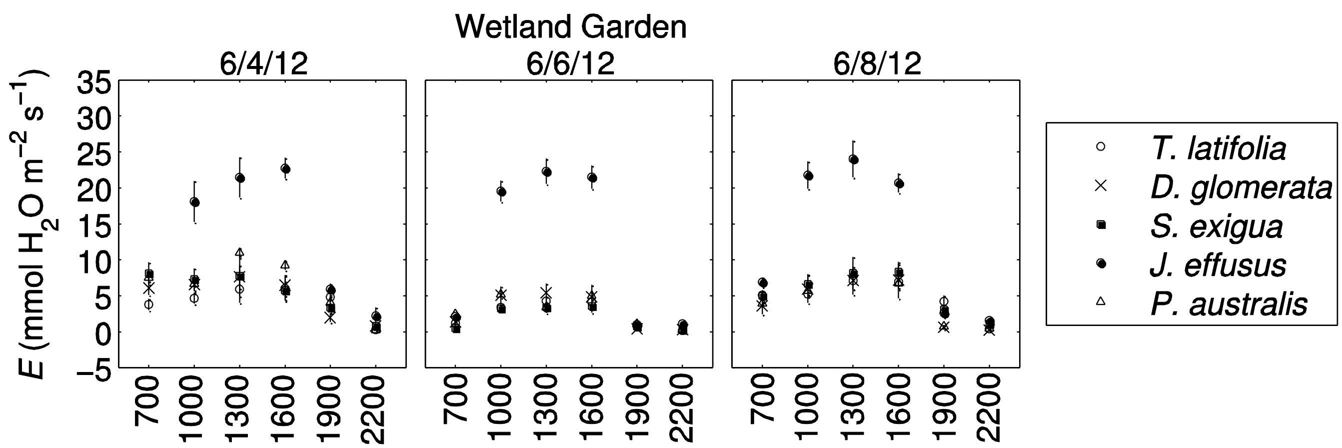

Figure 16. Transpiration rate (E mmol H_2O m^{-2} s^{-1}) for simulated Wetland June storm occurring 6/5/12

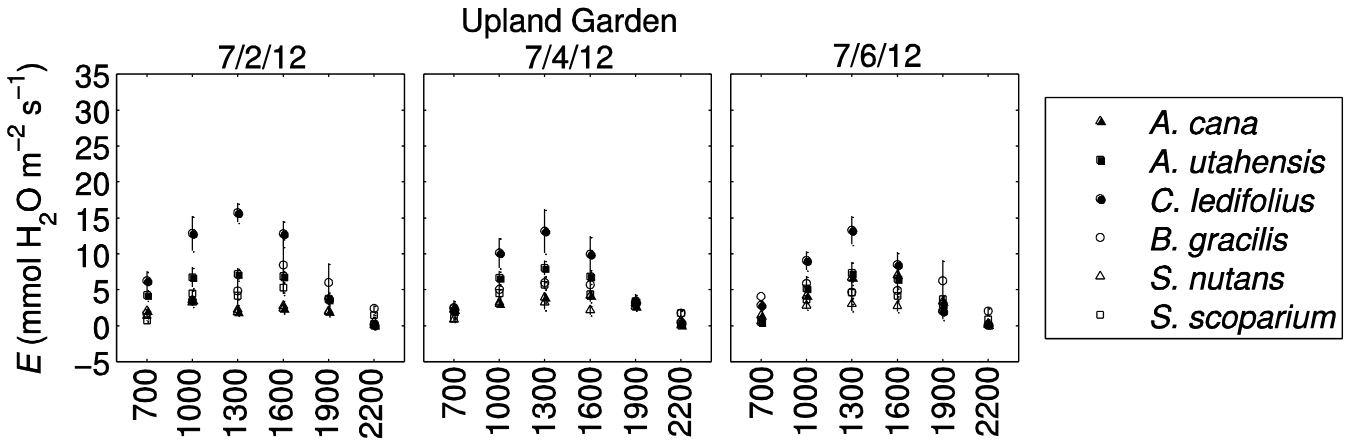

Figure 17. Transpiration rate (E mmol H_2O m^{-2} s^{-1}) for simulated Upland July storm occurring 7/3/12

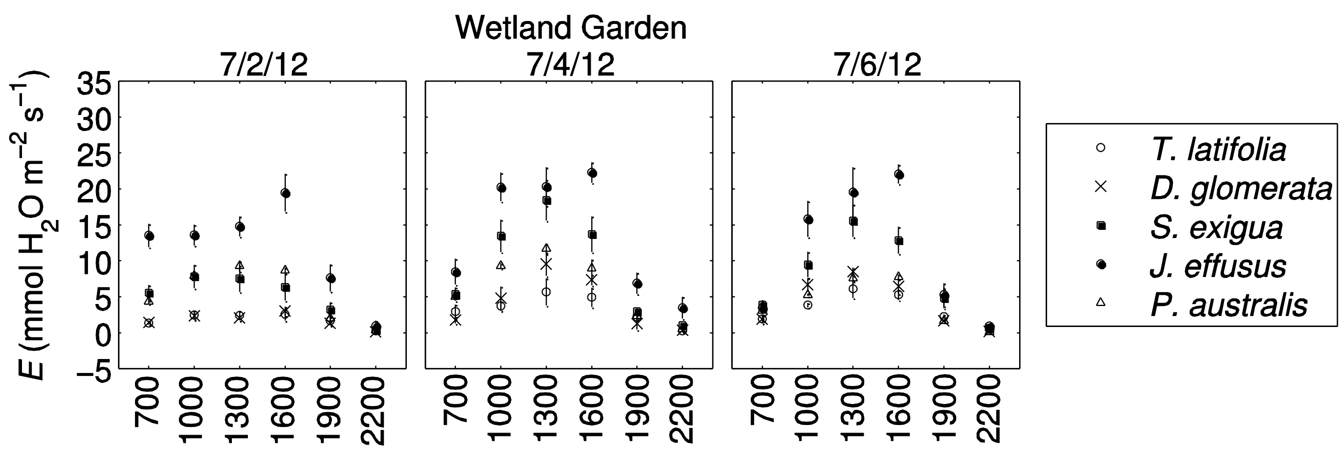

Figure 18. Transpiration rate (E mmol H_2O m^{-2} s^{-1}) for simulated Wetland July storm occurring 7/3/12

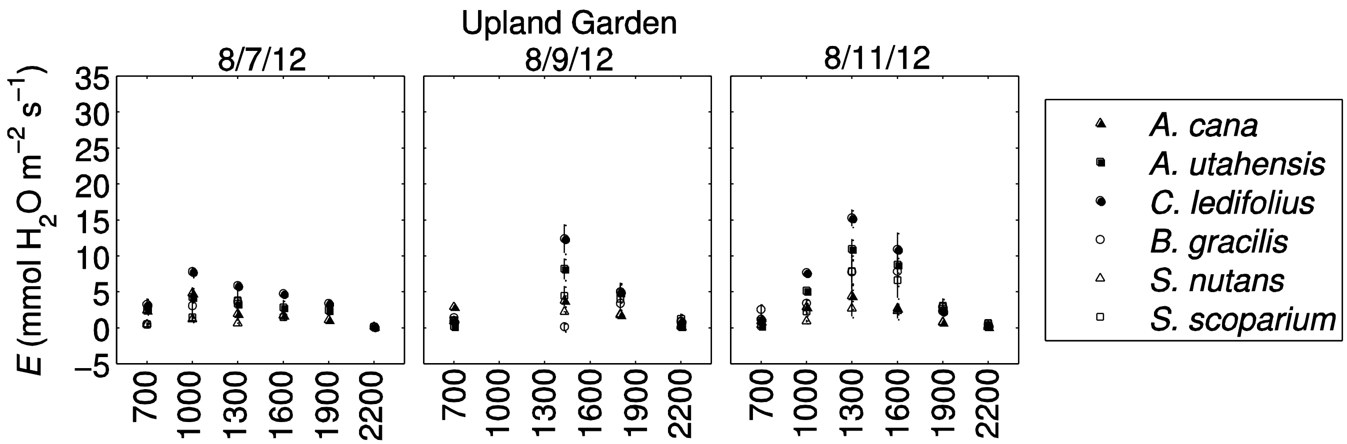

Figure 19. Transpiration rate (E mmol H_2O m^{-2} s^{-1}) for simulated Upland August storm which occurring 8/8/12

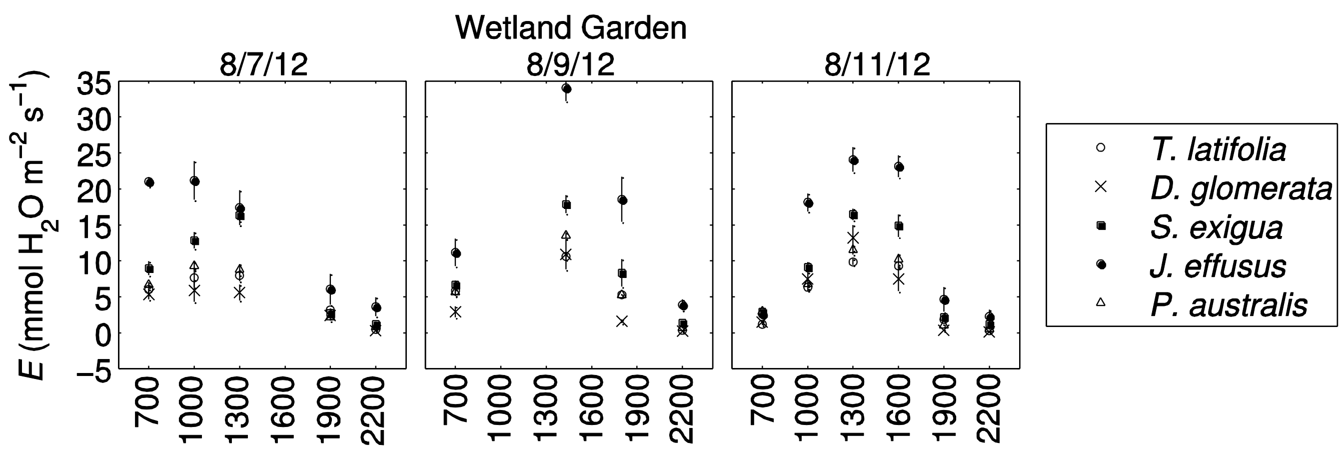

Figure 20. Transpiration rate (E mmol H_2O m^{-2} s^{-1}) for simulated Wetland August storm occurring 8/8/12

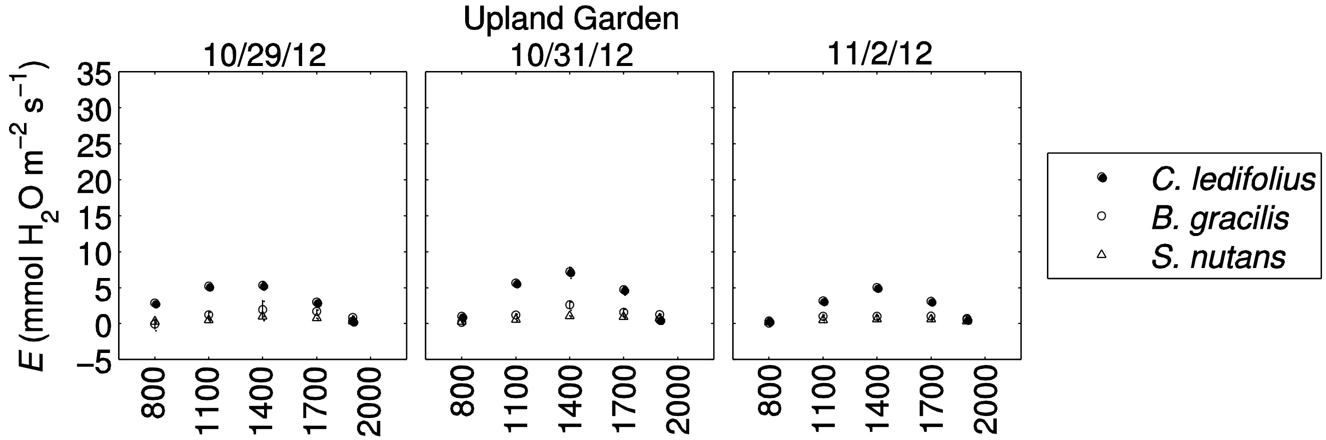

Figure 21. Transpiration rate (E mmol H_2O m^{-2} s^{-1}) for simulated Upland October storm occurring 10/30/12

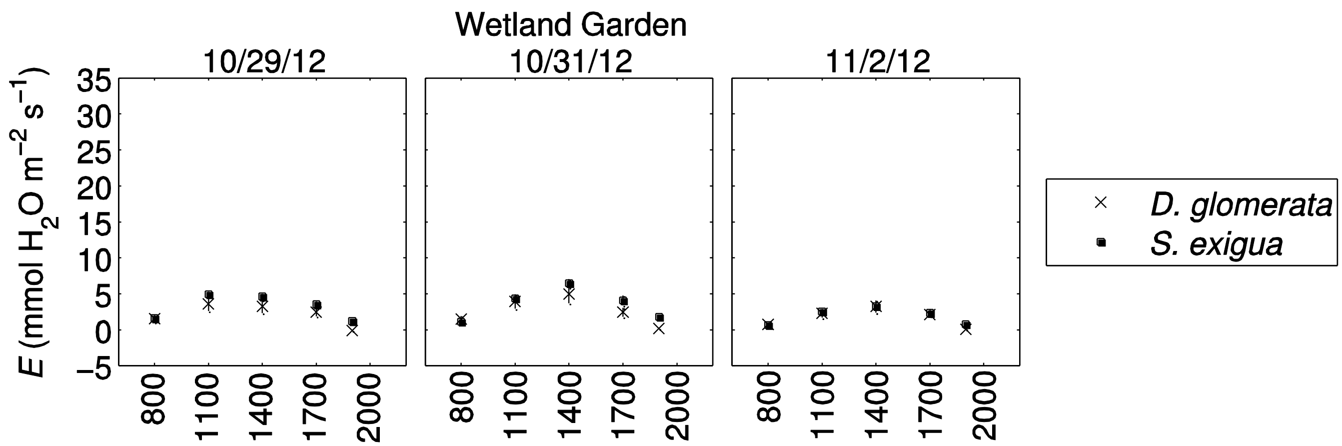

Figure 22. Transpiration rate (E mmol H_2O m^{-2} s^{-1}) for simulated Wetland October storm occurring 10/30/12

APPENDIX C

DAILY TRANSPIRED VOLUME

This appendix contains plots showing the daily transpired volume (DTV) from both the Upland and Wetland gardens for the months of May, June, July, August, and October. September was excluded from this study due to instrument maintenance. Note the difference in scale used for Upland and Wetland plots.

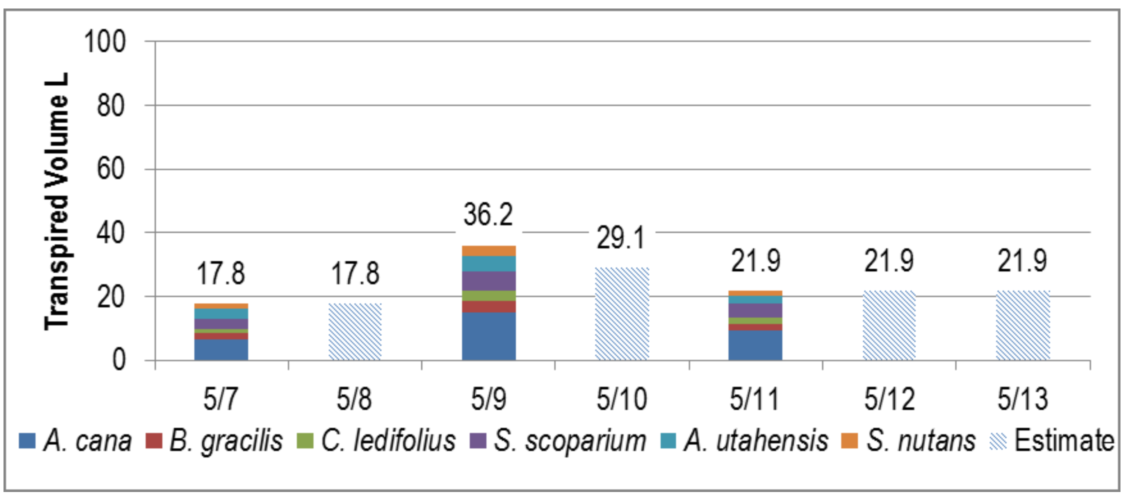

Figure 23. Measured and estimated volume transpired from Upland garden for simulated May storm event occurring 5/8/12
Note: Wetland garden DTV was not computed/estimated for the month of May.

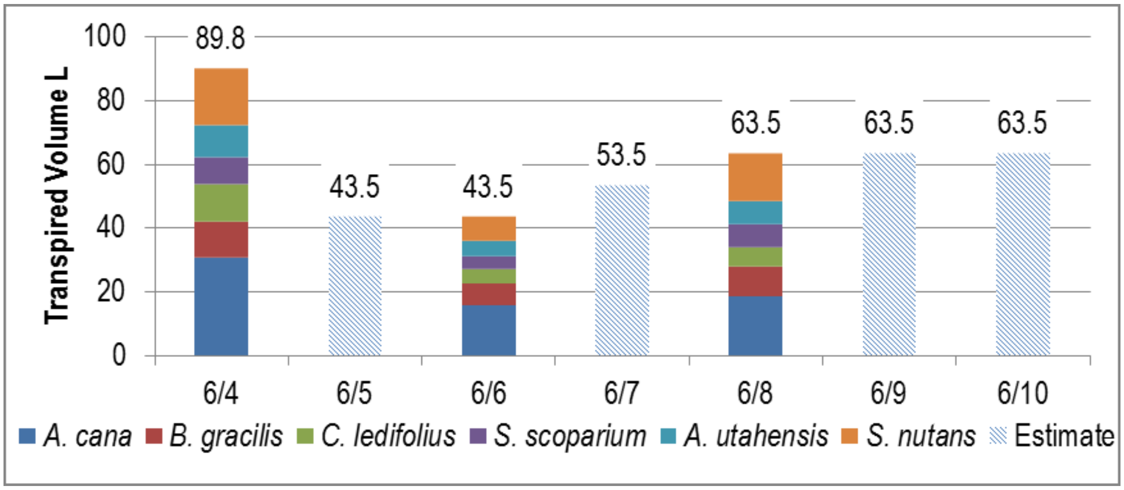

Figure 24. Measured and estimated volume transpired from Upland garden for simulated June storm event occurring 6/5/12

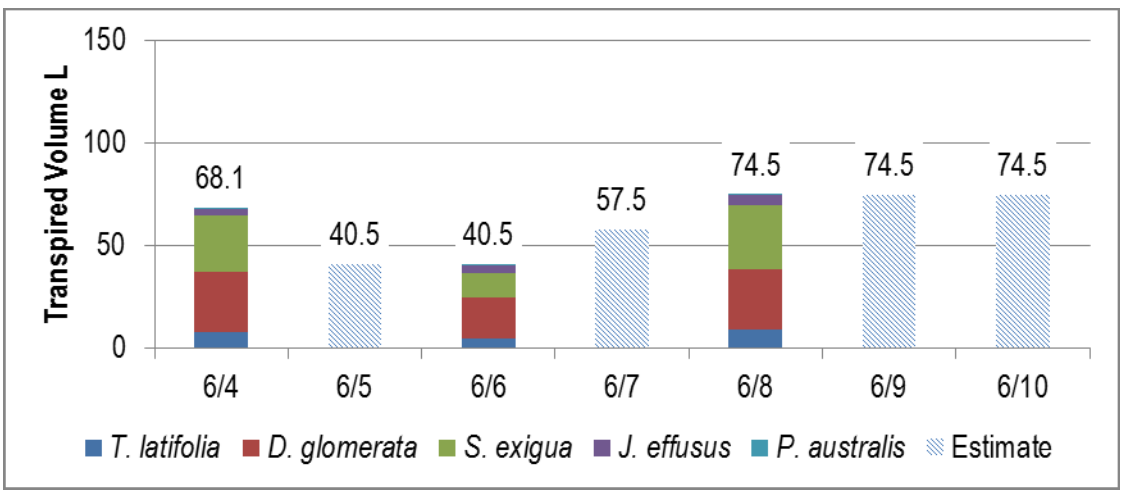

Figure 25. Measured and estimated volume transpired from Wetland garden for simulated June storm event occurring 6/5/12

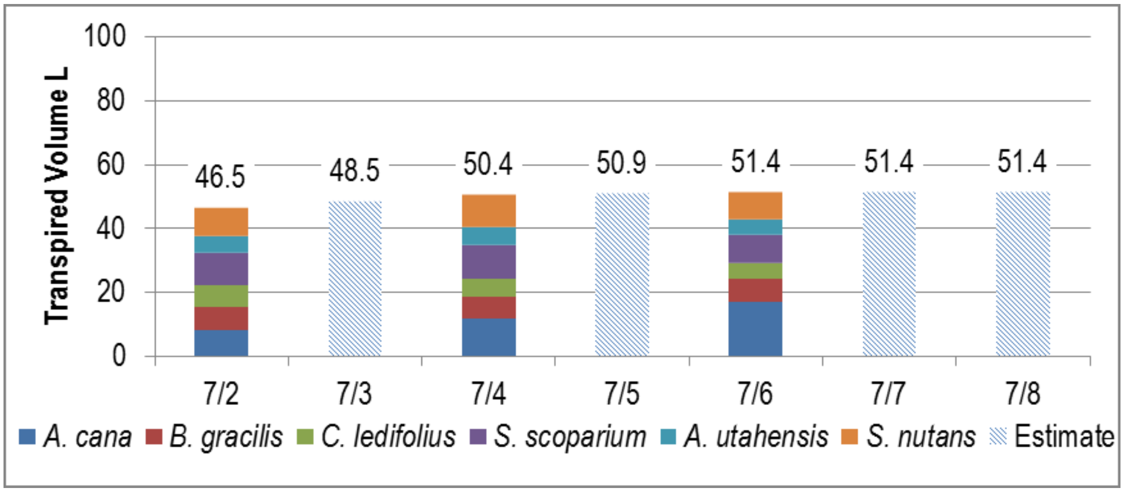

Figure 26. Measured and estimated volume transpired from Upland garden for simulated July storm event occurring 7/3/12

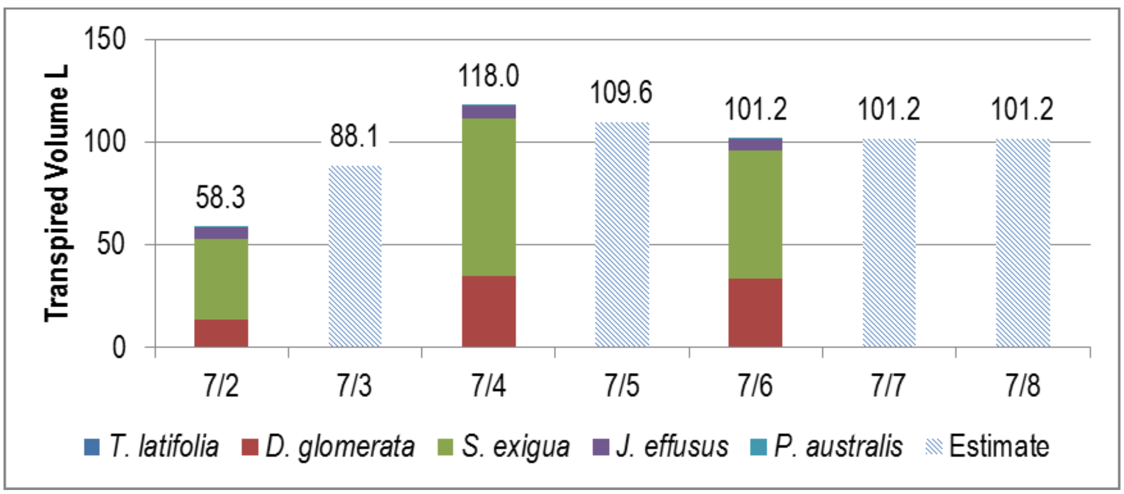

Figure 27. Measured and estimated volume transpired from Wetland garden for simulated July storm event occurring 7/3/12

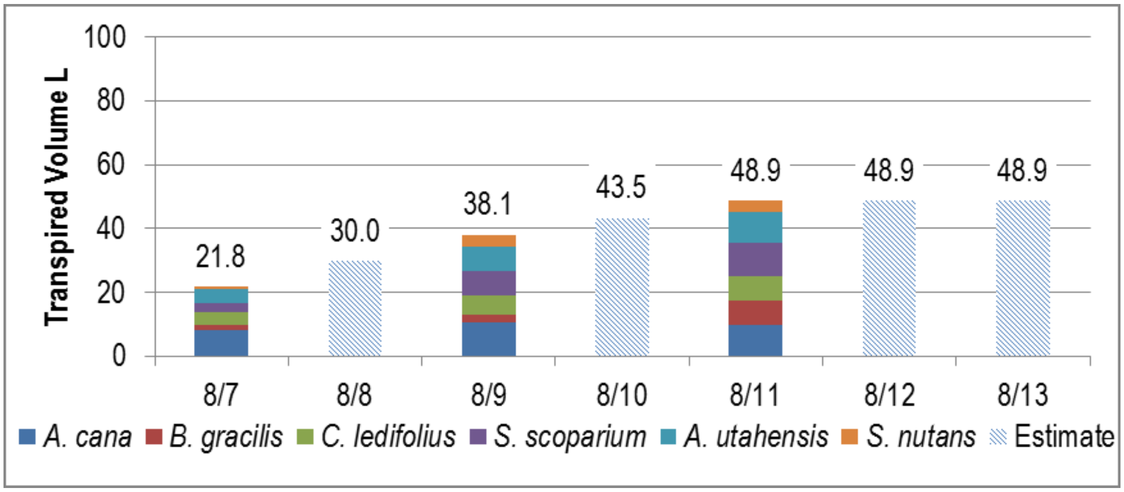

Figure 28. Measured and estimated volume transpired from Upland garden for simulated August storm event occurring 8/8/12

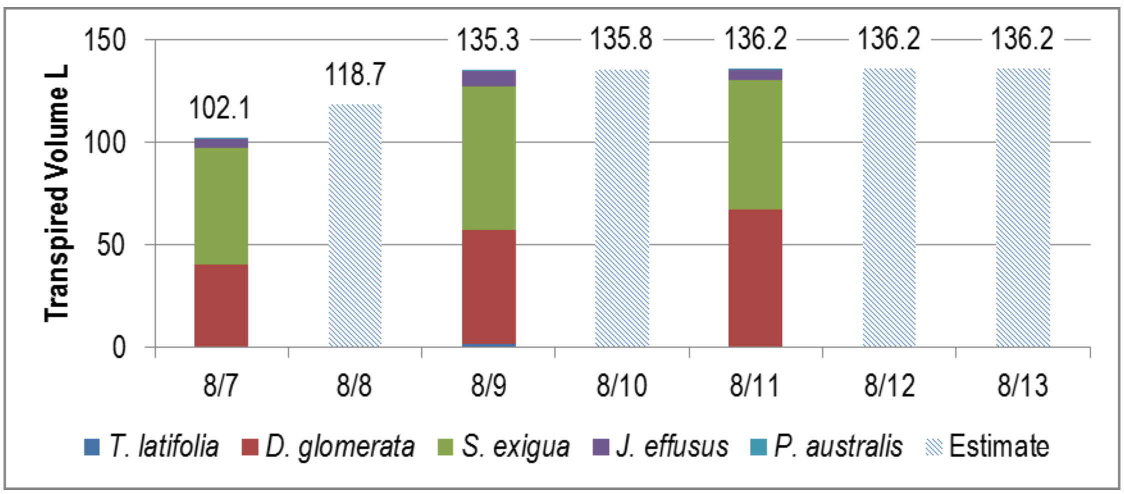

Figure 29. Measured and estimated volume transpired from Wetland garden for simulated August storm event occurring 8/8/12

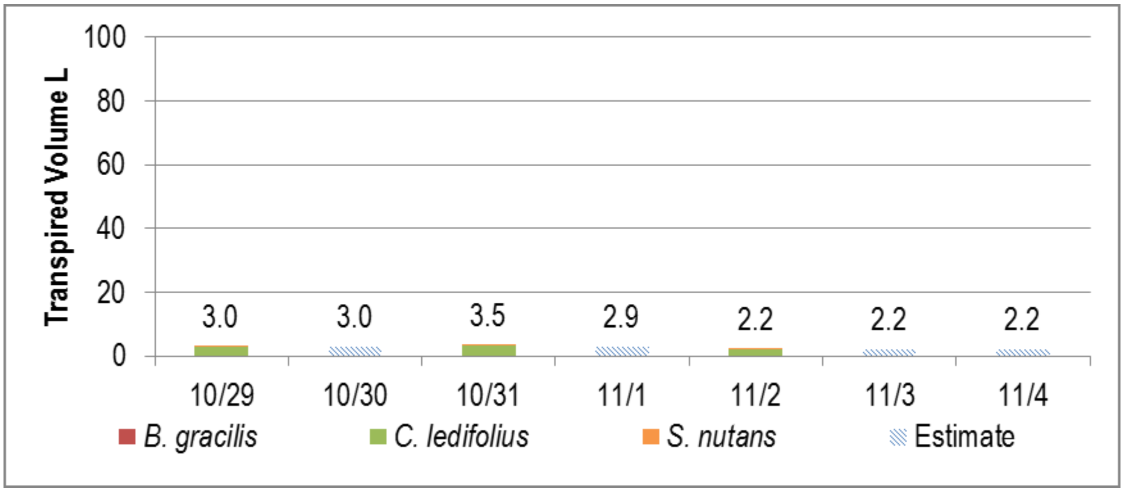

Figure 30. Measured and estimated volume transpired from Upland garden for simulated October storm event occurring 10/30/12

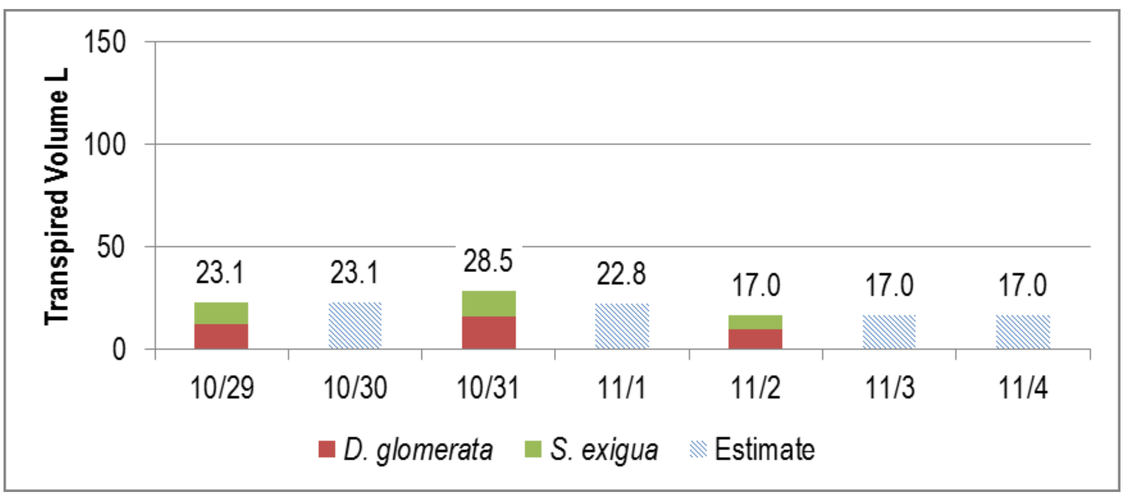

Figure 31. Measured and estimated volume transpired from Wetland garden for simulated October storm event occurring 10/30/12

APPENDIX D

STORM DATA USED FOR ANALYSIS

Because of instrument failure and some damage to the slope at the research site, the data for the tipping buckets do not match one to one with the storm events simulated. This appendix contains the storm records for which matching tipping bucket data were available.

Table 6. Stormwater inflow and drained outflow given in liters

	Target # of Storms	Control		Upland		Wetland	
		In	**Out**	**In**	**Out**	**In**	**Out**
Jan	5	1476	1518	1476	1288	1476	1499
		1476	1382	1476	1122	1476	1649
		1514	1508	1499	1260	1473	1398
		1514	1351	1473	1210		
Feb	5	1355	1342	1499	1285	1401	1376
		1601	1320	1287	1222	1507	1382
				1560	1112	1461	1360
				1435	*641	1590	1338
Mar	5	1787	1627	1772	1150	1351	1159
		1741	1441	1836	1024	1756	1323
		1711	1515	1794	1015	1632	*849
		1703	1593	1772	1021	1821	*757
		1817	*895	1790	1046	1809	1441
Apr	6	1919	1936	1919	1087	1919	1505
		1927	2007	1942	1115	1934	1519
		1927	2035	1942	1084	1919	1455
		1946	2092	1919	*2074	1987	1483
		1957	2049	1938	*2165	1934	1341
		1999	2035	1923	1505	1915	1144
May	5	1878	1901	1972	911	2018	1374
		1855	1986	1870	1150	1821	1525
		1874	*927	1874	1021	1874	1436
		1878	1890	1878	987	1878	1402
		1893	1971	1893	782	1893	1500
Jun	3	2006	1908	2006	697	2006	935
Jul	2	114	0	114	0	114	0
Aug	2	1514	490	1514	707	1514	434
Sep	3	1949	977	1949	710	1949	584
				1949	883	1949	988
				1949	952		

Table 6 Continued.

	Target # of Storms	Control In	Control Out	Upland In	Upland Out	Wetland In	Wetland Out
Oct	4	1874	1150	1874	974	1874	988
				1874	1181	1874	1566
Nov	4	1836	1475	1836	1330	1836	*2416
		1836	1370	1836	*760	1836	1291
Dec	5	1192	982	1192	779	1192	710
		1192	932	1192	1043	1192	1065
				1192	810	1192	613
				1192	851		

Note: Outliers are marked with a * and were not included in total annual water budget

REFERENCES

Atchley, A. L. and R. M. Maxwell, 2011. Influences of Subsurface Heterogeneity and Vegetation Cover on Soil Moisture, Surface Temperature and Evapotranspiration at Hillslope Scales. Hydrogeology Journal 19:289-305.

Barbour, M. G. and W. D. Billings, 1999. North American Terrestrial Vegetation, Cambridge University Press

Bolund, P. and S. Hunhammar, 1999. Ecosystem Services in Urban Areas. Ecological Economics 29:293-301.

Booth, D. B., 1990. Stream-Channel Incision Following Drainage-Basin Urbanization. JAWRA Journal of the American Water Resources Association 26:407-417.

Booth, D. B. and C. R. Jackson, 1997. Urbanization of Aquatic Systems: Degradation Thresholds, Stormwater Detection, and the Limits of Mitigation. JAWRA Journal of the American Water Resources Association 33:1077-1090.

Brown, L. R., T. F. Cuffney, J. F. Coles, F. Fitzpatrick, G. McMahon, J. Steuer, A. H. Bell and J. T. May, 2009. Urban Streams across the USA: Lessons Learned from Studies in 9 Metropolitan Areas. Journal of the North American Benthological Society 28:1051-1069.

Clausen, J. C., 2007. Jordan Cove Watershed Project. www. jordancove.uconn.edu/ jordan_cove/publications/final_report.pdf, *accessed* March 2013.

Coffman, L., R. Green, M. Clar and S. Bitter, 1993. Development of Bioretention Practices for Stormwater Management. Water Management in the 90's: A Time for Innovation, K. Hon, ed., ASCE, Seattle, WA, 126-129.

Costanza, R., R. d'Arge, R. De Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. V. O'neill and J. Paruelo, 1997. The Value of the World's Ecosystem Services and Natural Capital. Nature 387:253-260.

Davis, A. P., 2008. Field Performance of Bioretention: Hydrology Impacts. Journal of Hydrologic Engineering 13:90-95.

Davis, A. P., 2009. Bioretention Technology: Overview of Current Practice and Future Needs. Journal of Environmental Engineering 135:109-117.

Davis, A. P., M. Shokouhian, H. Sharma and C. Minami, 2001. Laboratory Study of Biological Retention for Urban Stormwater Management. Water Environment Research 73:5-14.

Emerson, C. H., C. Welty and R. G. Traver, 2005. Watershed-Scale Evaluation of a System of Storm Water Detention Basins. Journal of Hydrologic Engineering 10:237-242.

Groffman, P. M., D. J. Bain, L. E. Band, K. T. Belt, G. S. Brush, J. M. Grove, R. V. Pouyat, I. C. Yesilonis and W. C. Zipperer, 2003. Down by the Riverside: Urban Riparian Ecology. Frontiers in Ecology and the Environment 1:315-321.

Houdeshel, C. D., C. A. Pomeroy and K. R. Hultine, 2012. Bioretention Design for Xeric Climates Based on Ecological Principles. JAWRA Journal of the American Water Resources Association 48:1178-1190.

Hunt, W., A. Jarrett, J. Smith and L. Sharkey, 2006. Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina. Journal of Irrigation and Drainage Engineering 132:600-608.

Hunt, W. F., 2008. Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, N.C. Journal of Environmental Engineering 134:403-408.

Kolb, K. J. and J. S. Sperry, 1999. Transport Constraints on Water Use by the Great Basin Shrub, Artemisia Tridentata. Plant, Cell & Environment 22:925-935.

Leopold, L. B., 1968. Hydrology for Urban Land Planning: A Guidebook on the Hydrologic Effects of Urban Land Use, United States Department of the Interior

MacMahon, J. A., 2000. Warm Deserts. In: North American Terrestrial Vegetation, M. G. Barbour and W. D. Billings. Cambridge University Press, New York, NY, pp. 285-322.

Meyer, J. L., M. J. Paul and W. K. Taulbee, 2005. Stream Ecosystem Function in Urbanizing Landscapes. Journal of the North American Benthological Society 24:602-612.

Nehrke, S. M. and L. A. Roesner, 2004. Effects of Design Practice for Flood Control and Best Management Practices on the Flow-Frequency Curve. Journal of Water Resources Planning and Management 130:131-139.

Prince George's County, 1999. Low-Impact Development Design Strategies: An Integrated Design Approach. Department of Environmental Resources, Prince George's County, Maryland.

Shuster, W. D., M. A. Morrison and R. Webb, 2008. Front-Loading Urban Stormwater Management for Success – a Perspective Incorporating Current Studies on the

Implementation of Retrofit Low-Impact Development. Cities and the Environment 1:8-15.

United Nations, 2012. Population Division: World Urbanization Prospects, the 2011 Revision. Department of Economic and Social Affairs. New York.

USEPA, 2010. Green Infrastructure Case Studies: Municipal Policies for Managing Stormwater with Green Infrastructure. Washington, DC.

Walsh, C. J., T. D. Fletcher and A. R. Ladson, 2005a. Stream Restoration in Urban Catchments through Redesigning Stormwater Systems: Looking to the Catchment to Save the Stream. Journal of the North American Benthological Society 24:690-705.

Walsh, C. J., A. H. Roy, J. W. Feminella, P. D. Cottingham, P. M. Groffman and R. P. Morgan, 2005b. The Urban Stream Syndrome: Current Knowledge and the Search for a Cure. Journal of the North American Benthological Society 24:706-723.

Wenger, S. J., A. H. Roy, C. R. Jackson, E. S. Bernhardt, T. L. Carter, S. Filoso, C. A. Gibson, W. C. Hession, S. S. Kaushal, E. Martí, J. L. Meyer, M. A. Palmer, M. J. Paul, A. H. Purcell, A. Ramírez, A. D. Rosemond, K. A. Schofield, E. B. Sudduth and C. J. Walsh, 2009. Twenty-Six Key Research Questions in Urban Stream Ecology: An Assessment of the State of the Science. Journal of the North American Benthological Society 28:1080-1098.

West, N. E. and J. A. Young, 2000. Intermountain Valleys and Lower Mountain Slopes. In: North American Terrestrial Vegetation, M. G. Barbour and W. D. Billings. Cambridge University Press, New York, NY, pp. 285-322.

Young, D. R. and P. S. Nobel, 1986. Predictions of Soil-Water Potentials in the North-Western Sonoran Desert. Journal of Ecology 74:143-154.